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AN EVALUATION OF AUTOMATED CONTROL OF THE OXYFUEL CUTTING PROCESS FOR M1 VEHICLE FABRICATION

CONTRACT NUMBER DAAE07-82-C-4058

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by General Dynamics
Land Systems Division

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U.S. ARMY TANK-AUTOMOTIVE COMMAND
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Parameters were isolated to show potential use for fully automated real-time closed loop control of oxyfuel cutting of armor plate. Acoustic and temperature monitoring systems were established and demonstrated to be feasible for adaptive control equipment. Increased speed and improved cut quality were realized.

1.0 INTRODUCTION

General Dynamics Land Systems Division conducted a feasibility study evaluating automated control of the oxyfuel cutting process for use in fabrication of the M1 vehicle at the Lima Army Tank Plant. These efforts were performed under contract DAAE07-82-C-4058.

The nature of these tasks led the contractor to consult with the manufacturers of the oxyfuel gas cutting process equipment presently installed at the Lima Army Tank Plant. These manufacturers are Victor Equipment Company of Denton, Texas and ESAB Heath Gas Cutting Division of Fort Collins, Colorado.

Southwest Research Institute (SWRI), an established facility with over 2,000 employees involved in a broad spectrum of applied scientific and technological programs, was then contracted to address this application of current state-of-the-art sensing and control techniques for automated control of flame cut quality. Their report is included as the appendix to this report. This report contains a summary and a discussion of their results as well as conclusions and recommendations.

2.0 OBJECTIVES

The scope of the efforts performed by SWRI and presented in Appendix A includes isolation of the parameters that affect the cutting process and cut quality, determination of the variables with the greatest potential for use as process control inputs for an automated control system, and development of a method to monitor the flame cut process to allow these tasks to be completed.

3.0 CONCLUSIONS

Among the significant findings of the SWRI report are:

(1) The metal temperature is the "common denominator of all cutting problems."

(2) Relative spectral radiance of the flame cutting front can be monitored optically in the kerf.

(3) The relative spectral radiance of the kerf can be analyzed, correlated, and is "a very sensitive indicator of kerf temperature."

(4) The monitored spectral radiance provides advance indication of cut degradation.

(5) The simple logic sequence presented can be used with this advance indication of cut degradation to determine the cutting parameter which requires correction.

(6) Optical monitoring of the metal temperature at two points in the kerf by means of spectral analysis could possibly function as the input for automated control of flame cut quality.

4.0 RECOMMENDATIONS

In addition to these findings, the SWRI report contains a description of a realtime closed loop control system concept and some recommendations for further development. These recommendations are:

(1) A closed loop control system proof test model should be constructed and evaluated.

(2) After a successful demonstration of the proof test model, a production pilot model should be built and then evaluated at the Lima Army Tank Plant followed by final production model installation on all cutting machines at the Lima Plant.

5.0 DISCUSSION

Based on the materials presented in the SWRI report, General Dynamics believes the control system concept described shows enough technical merit to justify further effort; however, other factors should also be considered when reviewing these recommendations.

The first additional consideration is referred to in the contract as advantages, disadvantages and the probability of success. The advantages are clear.

The stated purpose of this investigation and the main advantage of developing automated control for the oxyfuel cutting process is improved quality. The other advantages such as higher production rates, higher productivity per station, lower costs, reduction of surface preparation rework resulting from gouging and slag formation, and reduced dependence on individual operator skill all relate to quality improvements. Successful adaptation of automated control for this process would not only benefit the M1 vehicle, but has potential applications industry-wide and would serve as the prototype for further applications.

Upon reviewing the SWRI report, the disadvantages are much less evident. As a minimum, it is presumed that increased sophistication of the control system would require a higher level of training in the area of maintenance.

A further assessment of the probability of success requires an evaluation of the technical risks attendant in transforming a control system concept into a physical reality. A key factor in making this assessment, which would be accomplished in the proposed program Phase IIa, is successful demonstration of control loop closure and the real-time aspects of the control concept. Potential savings, implementation requirements and costs, and the return on investment (ROI) are similarily contingent on successful control loop closure and operability in the production environment. The scope of this contract ended at a description of a workable control system concept. The proposed physical working system, the next task for development, will permit this report's rough cost estimates to be further refined. These cost related factors are discussed in the following sections.

5.1 POTENTIAL SAVINGS

Automated control of the oxyfuel flame cutting process presents three major areas of savings at the Lima Army Tank Plant. They are reduced cutting cycle time, reduced rework and reduced grinding.

The area of greatest potential savings is the reduction of flame cutting cycle time. Although flame cut quality improvement was the primary reason for this program, it was also observed that the flame cut rate could be increased significantly. This improvement, as well as possible reductions in torch set-up time and in preheating time, should provide a significant reduction in the flame cut cycle time.

Torch set-up time should be reduced because the automatic controls adjust the flame automatically for each new plate. This eliminates the time required for the operator to manually observe, listen and adjust the equipment to achieve a "good" flame. The set-up time factor is even more significant for multiple-torch cutting, especially where more than one cutting head is involved. In addition to compounding the number of adjustments, time is generally wasted in bringing the preheat temperature of each head into unison so the cutting oxygen can be turned on.

In addition to saving torch set-up and preheating time, the actual cutting speed should also be increased. Because the automated controls optimize process set-up, parts can be cut at the maximum speed allowed by the physics of the cutting process and not just the speed where the process will work and not lose the cut.

Indications are that process cycle speeds far in excess of these currently obtained are possible. Conservatively, the oxyfuel cutting process cycle speeds could be increased by at least 20%, which corresponds to a 17% reduction in cycle time.

The second area of cost reduction is in grinding time. Improved cut quality should result in a minimum of 10% reduction in grinding time.

In the same manner, rework attributable to flame cutting defects should be reduced. At the present time six (6) persons are assigned to rework flame cut parts. Quality improvements could possible reduce these needs to two (2) persons which corresponds to a 67% reduction in rework time.

The next consideration involves the cost reductions resulting from the potential time savings for adapting automated control of the oxyfuel process in the Lima Army Tank Plant. There are two elements of cost which must be considered. They are labor cost and the cost of equipment and facilities. Increased cutting speed will also decrease the cost of inventory, but this is an added plus that is not being considered here.

The cost of labor in flame cutting, rework and grinding is approximately $30 per hour. The cost of equipment and facilities in the flame cut area is in excess of $10 million with a life of no more than 10 years. Calculated over 10 years the equipment cost is approximately $50 per hour based on a one-shift operation.

These are real costs which the US Army will see in the form of equipment refurbishment and/or new equipment. By saving time, the US Army will save money by either extending the life of the current investment or by achieving increased output with less refurbishment investment. In any case, one could justify in excess of $80 per hour for labor and equipment cost in the flame cut area. The ROI analysis assumes $80 per hour. The rework and grinding area equipment requirements are negligible, therefore, the evaluation assumes $30 per hour for labor only.

Engineering estimates of the labor hours spent on the various operations are as follows:

Flame cut	34.1 hours
Grinding	25.9 hours
Rework	16.0 hours

Applying the time reduction, each area would save the following per tank:

Flame cut	34.1 x 17% = 5.8 hours
Grinding	25.9 x 10% = 2.6 hours
Rework	16.0 x 67% = 10.6 hours

Converting hours to dollars based on the combined labor and equipment rates discussed, the potential savings per M1 tank are as follows:

Flame cut	5.8 hours x $80 =	$464
Grinding	2.6 hours x $30 =	$ 78
Rework	10.6 hours x $30 =	$318
Potential savings per tank total		$860

5.2 IMPLEMENTATION REQUIREMENTS AND COSTS

The projected costs for implementation of the automated control for the oxyfuel cutting process are listed below and are divided into phases corresponding to anticipated major milestone tasks. These costs are based on rough estimates provided by the major participants in this program who are: General Dynamics Land Systems Division, ESAB Heath Gas Cutting Division, Victor Equipment Company and Southwest Research Institute. These budgetary costs are provided as an approximation of the return on investment potential.

5.3 IMPLEMENTATION REQUIREMENT		ESTIMATED COST
Phase I	Oxyfuel Cutting Process Automated Control Study	$ 134,000
Phase IIa	Proof Test Model Demonstration of Automated Control System	360,000

Phase IIb	Prototype Adaptation of Automated Control on a Lima Production Machine	418,000
Phase III	Installation of Automated Control on Remaining 9 Lima Production Machines	362,000
	TOTAL COST	$1,274,000

5.4 RETURN ON INVESTMENT (ROI)

The return on investment in terms of the number of tanks required to be built to recover the program cost is as follows:

$$\frac{\$1,274,000 \text{ program cost}}{\$ \quad 860 \text{ savings per tank}} = 1,481 \text{ tanks}$$

At a production rate of 60 tanks per month, the return on investment period would be as follows:

$$\frac{1,481 \text{ tanks}}{60 \text{ tanks per month}} = 24.7 \text{ months}$$

5.5 CONCLUSIONS AND RECOMMENDATIONS

Based on technical and economic factors, automated control of the oxyfuel cutting process using optical monitoring of the metal temperature at two points in the kerf as the control input is a strong candidate for further study.

In addition, the stated purpose of this investigation and the main advantage of developing automated control for the oxyfuel cutting process is improved quality. The other advantages such as higher production rates, higher productivity per station, lower costs, reduction of surface preparation rework resulting from gouging and slag formation, and reduced dependence on individual operator skill all relate to quality improvements. Successful adaptation of automated control for this process would not only benefit the M1 vehicle, but has potential applications industry-wide and would serve as the prototype for further application.

APPENDIX

A FEASIBILITY STUDY TO EVALUATE THE OXYFUEL GAS CUTTING PROCESS

FINAL REPORT
SwRI Project 7234

Prepared for

Victor Equipment Company
Airport Road
P. O. Box 1007
Denton, Texas 76201

Prepared by

Quality Assurance Systems and Engineering Division

March 1983

SOUTHWEST RESEARCH INSTITUTE
SAN ANTONIO HOUSTON

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SOUTHWEST RESEARCH INSTITUTE
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1. EXECUTIVE SUMMARY

In September 1982, Southwest Research Institute (SwRI) was contracted by Victor Equipment Company to conduct a feasibility study to evaluate the oxyfuel gas cutting process. Specific objectives of the project were:

(1) To isolate the parameter(s) that show potential for use as process control signals.

(2) To outline process control options from a relatively simple open loop control to a more sophisticated, fully automated, real-time closed loop control.

The feasibility study, conducted at SwRI, employed acoustic and temperature monitoring systems for evaluating single torch perpendicular and bevel cuts, and triple torch cuts. The acoustic monitoring employed two high frequency (0-500 kHz) acoustic sensors and one acoustic microphone in the audible frequency range. One of the high frequency acoustic sensors was mounted on the plate and the other on the cutting torch. The airborne noise was monitored by a microphone. Temperature monitoring in and around the kerf was conducted in both the visible and the infrared ranges using video cameras and fiber optic systems.

The results of the feasibility study have shown that spectral radiance (temperature) in the infrared range near the top and bottom of the cutting front could provide control signals to minimize gouging and slag formation. The results of the acoustic monitoring have demonstrated that a high frequency acoustic sensor on the torch could be used to detect abnormal tip/torch behavior. Additionally, a high frequency sensor on the plate could be used to monitor gouging as well as excessive slag adhering conditions. However, since this method works after the fact, i.e., after gouging has initiated, the temperature monitoring method is considered more suitable.

The experimental data, supported by the literature review, lead to the conclusion that the common denominators of all flame cutting problems are the temperature at the cutting front and the iron-oxygen mixture ratio. The flame cutting parameters are interrelated because cutting speed affects both the temperature at the cutting front and the iron-oxygen mixture ratio, while preheat input energy affects the temperature at the cutting front and the cutting oxygen flow affects the iron-oxygen mixture ratio.

A real-time closed loop system is described in this report. It is highly recommended that such a closed loop proof test model be developed and tested; and, after a successful demonstration of the proof test model, that a prototype model be built, and evaluated at the Lima Army Tank Plant before making production models and installing them on all the cutting machines at the Lima Plant.

The details of the feasibility study are provided in this report under the following major headings: problem description, literature review, experimental setup, data acquisition, data analysis, discussion of results, conclusions and recommendations.

2. ACKNOWLEDGEMENTS

The authors wish to thankfully acknowledge the help and cooperation of David Reed, Ed Ramon, Robert Spinks, and Vic Schick for experimental work, and Roger Zwicker, Jack Minser, and Ben Jezek of Victor Equipment Company for supplying cutting equipment and providing assistance in the flame cutting operation. Thanks are also due to Terry Whalen of ESAB-Heath for many helpful suggestions and encouragement, and to Tony Plunkett, Milt Snyder and Mark Stein for providing armor plate material.

3. PROBLEM DESCRIPTION

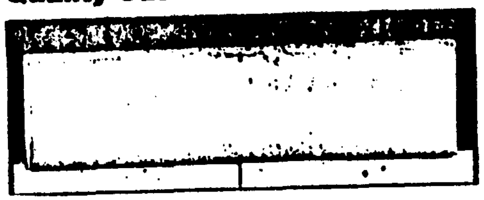
The process of oxyfuel cutting (OFC) (also known as burning, flame cutting, and flame machining) is routinely employed in cutting thick sections of material because it is fast, effective, and relatively inexpensive as compared to machining. However, an equally important reason for selecting one process over another is the quality of surface it produces on the finished cut; i.e., in many cases, the cut materials are used in fabrication with no other surface processing, and the quality of the surfaces is very significant.

While the cut surface quality is dependent on many variables, the most significant for the OFC process are (1): (1) intensity of the preheat flames and the preheat oxyfuel gas ratio; (2) size and shape of the cutting oyxgen orifice; (3) purity of the cutting oxygen; (4) cutting oxygen flow rate; (5) cleanliness and flatness of the exit end of the nozzle; (6) cutting speed; (7) type of steel; (8) thickness of the material; (9) quality of steel; and (10) condition of the steel surface.

For any given cut, the variables listed above have to be carefully evaluated to obtain the required quality cut at a minimum cost. Figure 3-1 shows typical edge conditions resulting from variations in the cutting procedure for material of uniform type and thickness (2).

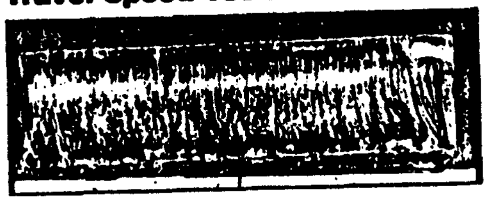
In order to obtain a high quality cut, tables and charts can be used to obtain process parameter information such as most suitable diameter of cutting orifice, cutting speed, gas flow rate, pressures, etc. for a given material thickness. However, these values are approximate and need to be determined for specific material. Furthermore, these tables and charts are based upon perpendicular, single torch cuts. The characteristics of bevel cutting and multiple torch cutting are, in many respects, very different from those of perpendicular cutting, and therefore most of the available data are not applicable. Ultimately, it is operator skill and proper selection, adjustment and operation of the cutting machines which are responsible for efficient production.

Quality Cut



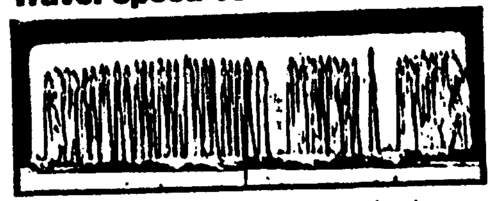
A quality cut produces a smooth finished plate surface that requires little, if any, additional finishing or conditioning. Edges are clean and square, and free of slag deposits.

Travel Speed Too Fast



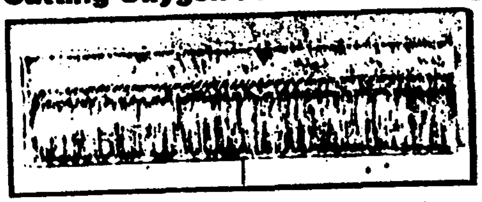
Top edge remains relatively clean and square, while considerable slag adheres at bottom, due to incomplete oxidation. Occasional gouges can be seen and pronounced draglines slant away from the direction of the cut.

Travel Speed Too Slow



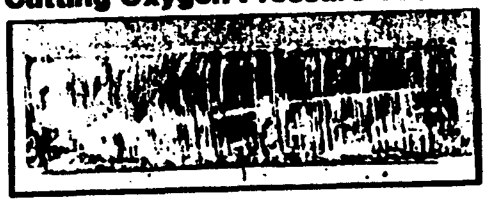
Top edges are rough and uneven due to prolonged exposure to the flames. Considerable slag usually adheres to the bottom edge. Severe pits and gouges are produced by the erratic wandering action of the high pressure oxygen stream.

Cutting Oxygen Pressure Too High



Top edge is uneven and "dished out" as the excessive pressure causes the oxygen stream to expand upon entering the plate. Plate face is relatively smooth and free of pits or gouges and slag is minimal. The sound of the cut is exceptionally loud.

Cutting Oxygen Pressure Too Low

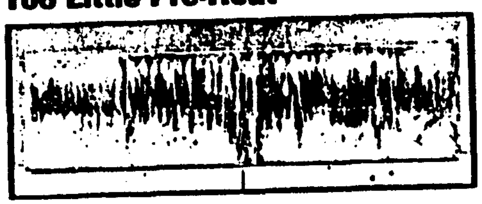


Lower portion of plate face is rough and somewhat gouged due to oxygen stream lacking sufficient pressure to penetrate. Considerable slag adheres to the bottom edge.

Too Much Pre-Heat

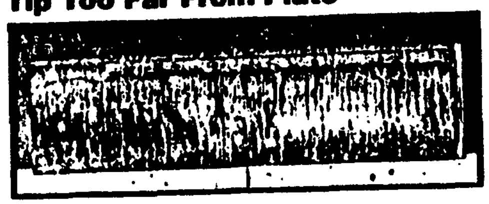
Top edge of plate shows rounded appearance and is somewhat melted away by the excessive preheat flame. Beads of molten metal form on top edge and considerable slag is produced due to the large amount of metal being melted away.

Too Little Pre-Heat



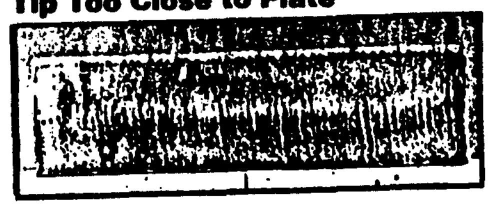
Top edge is slightly rounded and out of square. Occasional pits and gouges along with distinct draglines can be seen on the plate face.

Tip Too Far From Plate



Top edge shows signs of being blown away similar to the effect of too much oxygen pressure. Other aspects of plate appear satisfactory.

Tip Too Close to Plate



The preheat flames interrupt the cutting oxygen stream causing the upper portion to appear rough and uneven. Bottom edge is relatively free of slag. Occasional gouges may appear on the face of the plate.

FIGURE 3-1. CUT QUALITY AS A FUNCTION OF VARIOUS FLAME CUTTING PARAMETERS (2)

In the production environment, such as at the Lima Army Tank Plant, a large number of components with varying thicknesses and edge configurations (single vs. multiple torch, straight cut vs. bevel cut, etc.) have to be produced at relatively high rates, with good cut quality (so as to minimize rework). Furthermore, many of the parts have several different edge configurations and most nests have different parts with yet other edge preparations. Additionally, the flame cutting operator's ability to hear and see the cutting flames, by which a skilled operator adjusts cutting parameters, is impaired because of flame cutting setup, production noise environment, operation of two cutting heads at the same time, and distance between the operator and the cutting head. All this makes the flame cutting operator's job extremely difficult, and it is not surprising that a lot of rework to eliminate gouging and slag formation is required.

It is toward this problem of producing quality cuts during the flame cutting operation that this study is directed.

4. LITERATURE REVIEW

An elaborate literature search was conducted to determine the following:

- Physics of the flame cutting process.
- Specific cutting problems associated with the perpendicular, bevel and multiple torch cuts and their remedies.
- Methods to monitor and (possibly) control the flame cutting process.

The search was conducted through Metals Abstracts and the DIALOG information retrieval service data base offered by Lockheed Missiles and Space Company. The literature search revealed that relatively few scientific papers on the flame cutting process have been published through the years. Most of the literature was on single torch perpendicular cutting (1-7). Very little information was found on bevel cutting (8), triple torch cutting (1) and flame cut monitoring (11). A bibliography on the subject has been included in Appendix A for reference purposes. In this chapter, the flame cutting process and the effect of various process parameters on cut quality and flame cut temperature monitoring are discussed.

4.1 Physical Principles of Oxyfuel Gas Cutting Process

The oxyfuel gas cutting process involves an active exothermic reaction of the metal with high purity oxygen, with sufficient heat generation by the oxidation of metal, to continuously preheat the material ahead of the cutting flame. Chemically, iron when heated to its ignition temperature above 1535°C combines rapidly with high purity oxygen to oxidize as follows (1):

(i) $Fe + O \rightarrow FeO$ + heat release (267 kJ), first reaction

(ii) $3Fe + 2O_2 \rightarrow Fe_3O_4$ + heat release (1120 kJ), second reaction

(iii) $2Fe + 1.5O_2 \rightarrow Fe_2O_3$ + heat release (825 kJ), third reaction

The larger heat release of the second reaction predominates that of the first reaction. The third reaction occurs to some extent in heavier cutting applications. Figure 4-1 shows a schematic representation of the cutting process. Essentially the high purity oxygen jet is surrounded by preheat flames. The purpose of the preheat flames is to (1) heat the metal for initiation of the flame cutting process, (2) provide an additional heat source besides the exothermic reaction to sustain the cutting process, by maintaining a molten metal film and fluid slag, (3) shield the

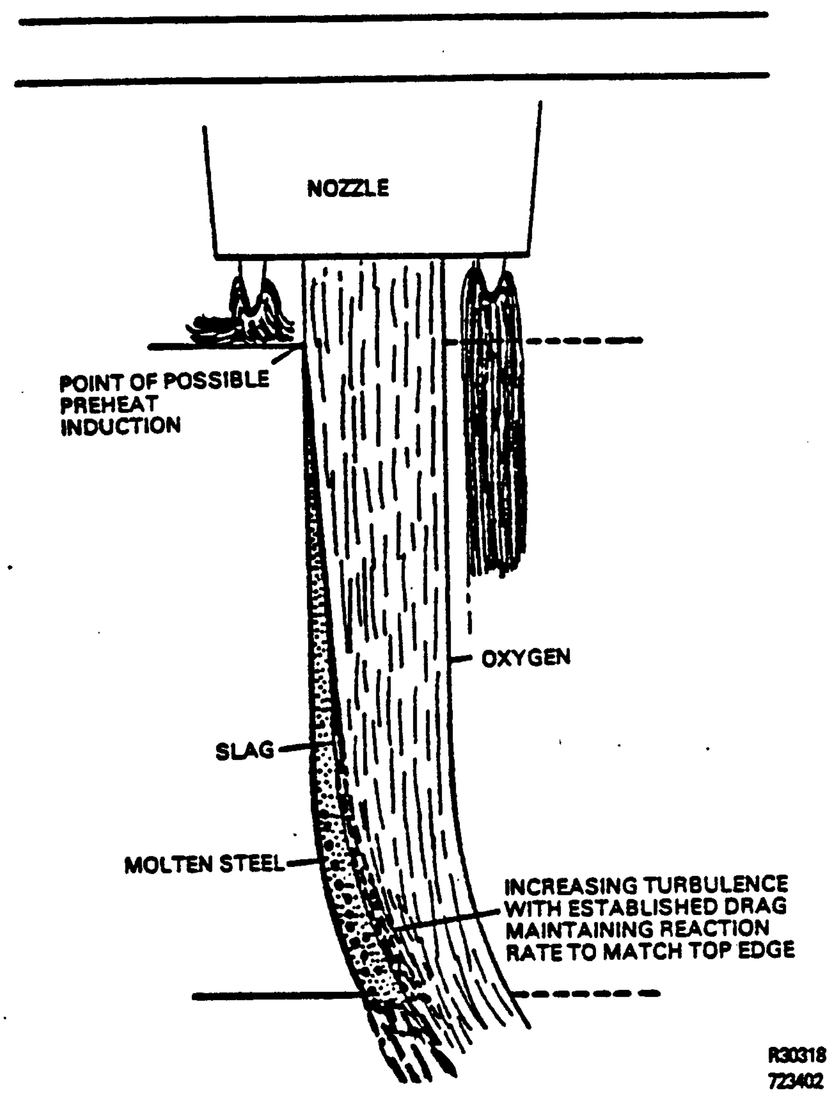


FIGURE 4-1. SCHEMATIC REPRESENTATION OF THE FLAME CUTTING PROCESS. Molten steel layer is present at the cutting front. High purity cutting oxygen diffuses through slag to oxidize iron (3).

high purity oxygen jet from turbulent interaction with air or contamination, and (4) dislodge rust or scale. The purpose of the cutting oxygen is to provide the oxidation reaction and to remove slag from the kerf.

The oxidation process begins at the top surface of the plate immediately below the cutting oxygen jet and progresses forward at the speed of the cutting torch and tip assembly. The oxygen jet travels in the through-thickness direction, partly oxidizing iron and converting it into oxide slag (causing oxygen jet momentum to decrease). Also, the proportion of gaseous impurities at the reaction surface increases, as does the amount of oxide slag in the through-thickness direction. The speed of cutting is determined by the speed at which the oxidation reaction at the bottom of the kerf can be sustained. Beyond a certain speed 'drag' develops because the reaction at the bottom of the kerf with the depleted oxygen supply is maintained at the same rate as at the top. This causes an increasing breakdown of the liquid molten metal film, and mixing by the increasing angle of incidence of the jet. As a result of the greater mixing and turbulence, there is gouging of the faces (3). Proper selection of cutting equipment (torches, tips, regulators, etc.) and process parameters (preheat fuel flow, cutting oxygen and speed, etc.), and proper adjustments are required to produce quality cuts (1,2,4).

Jezek (4) and others (1,2) point out that speed, cutting oxygen flow rates and preheat are critical to producing good quality cuts. An analysis of the available literature on the flame cutting process points to the fact that cutting speed, cutting oxygen flow rates and preheat conditions primarily affect temperature distribution in and around the kerf and the mixture of cutting oxygen and iron. The cutting parameters, and how they affect temperature distribution in the kerf or the cutting oxygen and metal mixture or both, are discussed in Subsections 4.1.1 and 4.1.2, with speed being a dependent variable.

4.1.1 Preheat

No more preheat is needed than required to bring the metal to kindling temperature (4). Several factors may affect the preheat input to bring the metal to kindling temperature. They are:

(1) Type of fuel gas
(2) Ratio of fuel gas to oxygen
(3) Pressure of preheat gases
(4) Tip type, size and height
(5) Cutting speed
(6) Thickness of plate
(7) Nesting
(8) Surface condition
(9) Chemical composition of material
(10) Angle of cut

Fay (5) and Anthes (6) have shown that type of fuel (propane vs. natural gas, etc.) and stoichiometric ratios significantly affect heat transfer intensity and therefore temperature distribution in a plate. Furthermore, the temperature distribution is dependent on preheat gas pressures, since the gas flow pressure is directly proportional to the velocity of the gases, and transfer of heat from flame to metal is partly dependent on the impingement of the hot gas molecules on the surface of the metal plate. The type and size of tip also influence heat transfer, since they contribute to gas flow (1,2). Fay and Anthes have also shown that the heat transfer intensity is greatly affected by the distance of the tip from the metal.

Higher cutting speed, obviously, lowers preheat and the quality of the cut goes down. The higher cutting speed may cause formation of excessive slag at the bottom of the cut that is hard to remove and/or leaves distinct drag line markings. The cut quality also goes down when the cutting speed is too slow. In this case, excessive gouging may occur, the top edge may roll over, thinner plates may warp and beads may form at the top of the plate. All these degradations in cut quality are related to excessive temperature of the plate and, in the case of gouging, to excess supply of cutting oxygen available for oxidation, which is further dependent on the temperature distribution.

Although thicker plates require more heat input, they do not require any more than absolutely necessary to bring the plate to kindling temperature. This aspect was researched and reported by Baikova and Sumrin (7). Their experimental and analytical results show that although heat input requirements for different thicknesses of material are different, the cutting process maintains a maximum temperature of 1200-1300°C. Their experiments were conducted on material thicknesses ranging from 12 mm (0.5 in) to 40 mm (≈1.5 in). Their analytical work also shows that approximately 66 percent of the energy for preheating is provided by preheating flame and 34 percent by the exothermic chemical reaction. It must be pointed out that for thicker materials lower preheat flame input may be required because of slower cutting speed (8) and also because of heat release (825 kilojoules of heat energy per centimeter) due to the formation of Fe_2O_3 (equation 3) (1).

Nesting could have significant affects on preheat requirements, depending on the size of the components to be cut, and the type and number of cuts. This is due to the fact that as the plate temperature rises, lower preheat is required (1). Antonov, Spektor and Shishlovskii (9) have shown a linear dependence of flame preheat transfer to the temperature of the plate (attained due to prior cutting or heating), i.e., the higher the plate temperature, the lower the preheat required.

Spies (8) has given a detailed analysis of bevel cutting. His results show that the preheat input requirements to achieve proper metal temperature for bevel cutting are significantly different from those for perpendicular cutting. Furthermore, the thinner material requires more preheat than the thicker material, as shown in Figure 4-2. One of the reasons for higher preheat requirements for bevel cuts is the relative

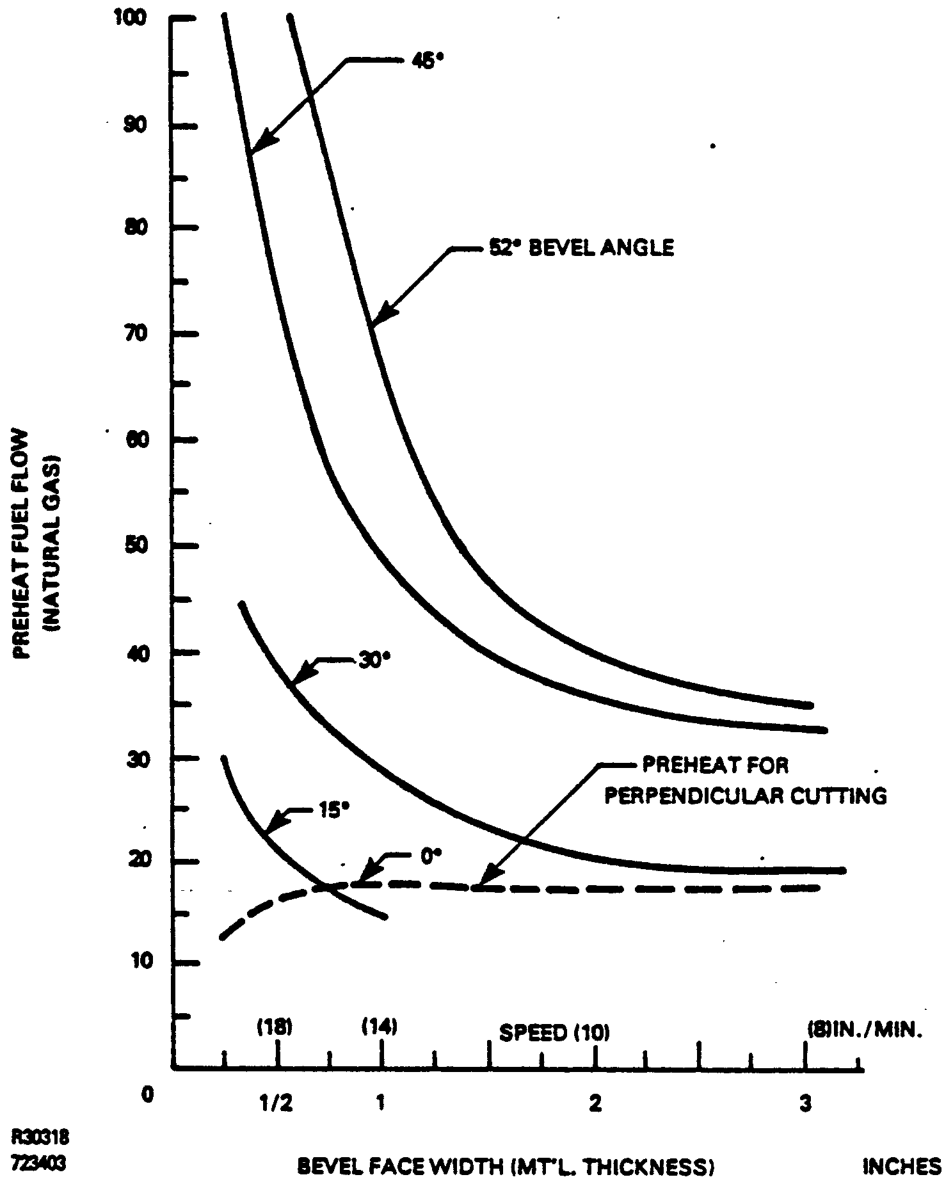


FIGURE 4-2. TYPICAL PREHEAT REQUIREMENTS FOR BEVEL CUTTING VARIOUS MATERIAL THICKNESSES (8)

area which is heated and the angle of impingement of the flame, as illustrated in Figure 4-3. The reason why thinner materials require 2-10 times higher preheat than thicker materials for the same bevel angle is not very apparent (8). Nevertheless, preheat input requirements for bevel cutting could be significantly different than those for perpendicular cutting.

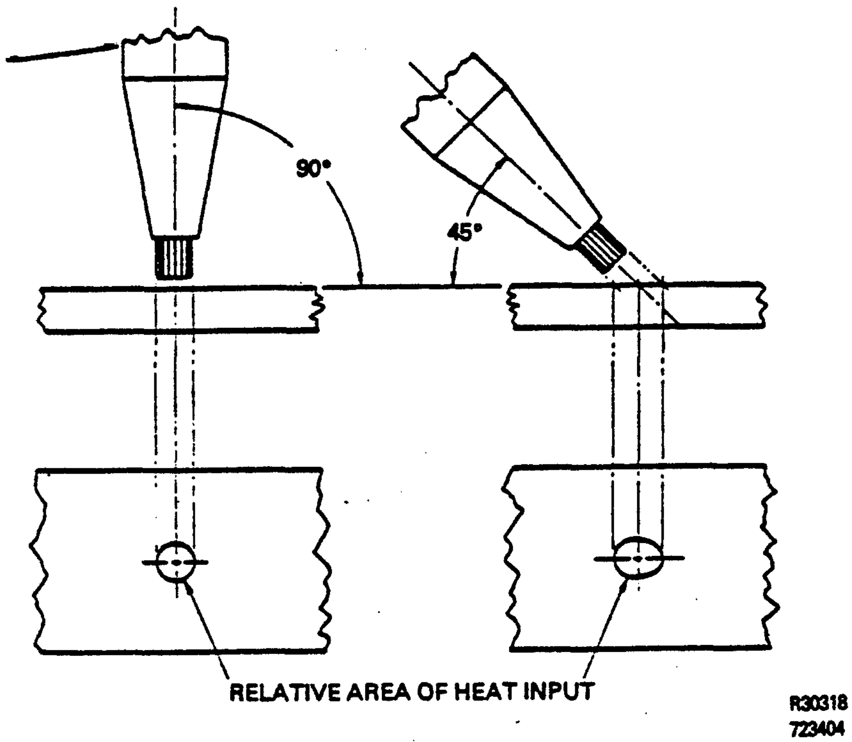


FIGURE 4-3. COMPARISON OF PREHEAT AREA IN PERPENDICULAR AND BEVEL CUTTING (8)

The above discussion demonstrates that most factors influence heat transfer from preheat flames to the plate, and since it is necessary to bring the plate to kindling temperature for the cut to proceed smoothly, temperature monitoring could be effectively used in a flame cutting process control system.

4.1.2 Cutting Oxygen

The function of the cutting oxygen is to provide the oxidation reaction and to remove molten slag from the kerf. If the cutting pressure is too high it causes too wide a kerf and the cut is generally poor quality because the face of the plate is rough and irregular, particularly near the top part of the cut. Additionally, some of the oxygen may blow back out of the kerf, depositing beads of molten metal on the top of the plate (4). With low oxygen pressure, it is often difficult to start a cut, since the cutting oxygen stream does not have enough force to oxidize all the way through the plate. The following factors influence the requirements for cutting oxygen:

(1) Cutting speed
(2) Tip size and type
(3) Pressure of cutting oxygen
(4) Purity of oxygen
(5) Thickness of plate
(6) Chemical composition of material

If the cutting speed is too low, availability of excessive oxygen combined with excessive preheat could cause gouging. This results in an uneven temperature distribution in the kerf. Therefore, temperature monitoring can indicate cut quality and could be used as a control of cutting parameters. Matsunawa et al. (11) have monitored the flame cutting process and demonstrated that the cutting flame extinguishes completely and ignites again under certain conditions. Figure 4-4 (11) shows relative temperature measurements as a function of time at five locations in the kerf. The ignition-extinction-reignition cycle is evident from this figure. If the cutting speed is too high, the cut may not get started or may be lost after it has been initiated. In other words, since the oxidation process does not occur appropriately the temperature must be affected, and therefore it should be able to act as a control signal.

Tip size and type determine the amount of oxygen that flows through the nozzle tip and its velocity. If the flow rates are too low the cutting oxygen stream may not be able to push out the molten slag from the kerf, thereby raising the temperature in the lower part of the kerf. On the other hand, if flow rates are too high the molten slag is pushed out of the kerf and the temperature is relatively lower in the lower part of the kerf (1,2,4).

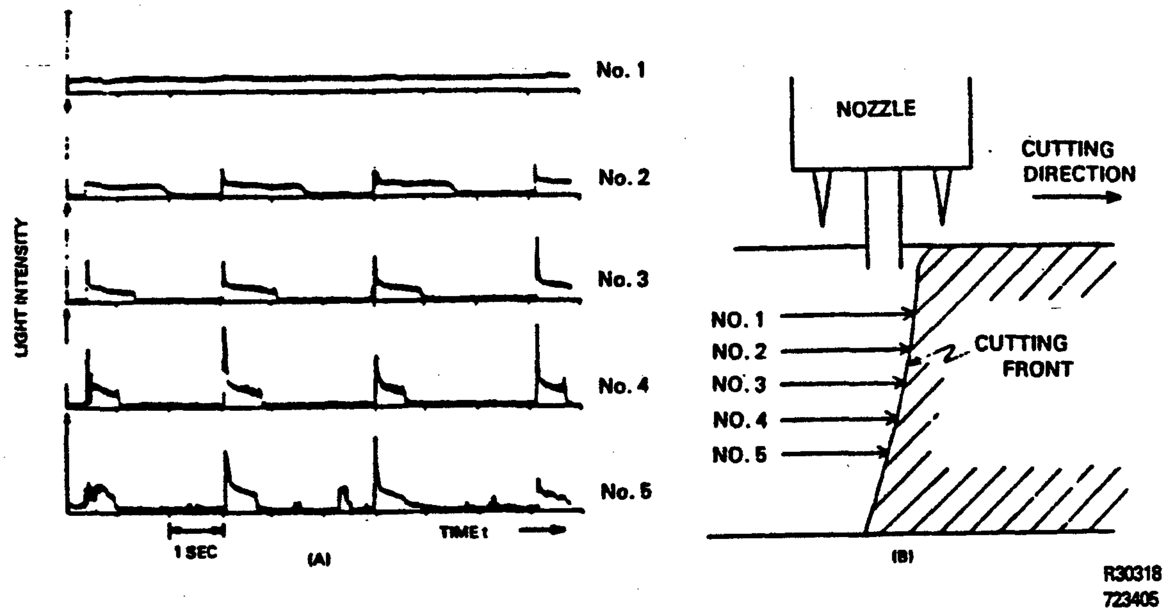


FIGURE 4-4. LIGHT SIGNALS EMITTED FROM CUTTING FRONT DURING NOTCHING (11). Light intensity (relative temperature) at five locations within the kerf as a function of time (a) showing extinction and re-ignition for sensor location Nos. 2 to 5.

The purity of cutting oxygen can have significant effects on cut quality and overall cutting efficiency. Lower purity reduces the efficiency of the cutting operation. A one percent decrease in oxygen purity will result in a decrease in cutting speed of approximately 15 percent and an increase of about 25 percent in the cutting oxygen consumption (1). Also, Wells (12) has shown that cutting efficiency significantly depends on carbon content of the steel. One percent of carbon in the steel had the same suppressive effect as 6.2 percent of nitrogen in the cutting oxygen. The increase in cutting oxygen and the reduction in cutting speed could be explained on the basis of the fact that more oxygen is required for oxidation purposes because of impurities; and also that less heat is released from the exothermic process and, therefore, more heat must be supplied by reducing the cutting speed.

Unlike preheat, the requirements of cutting oxygen in beveling are very similar to those of perpendicular cutting. The cutting oxygen requirements in beveling have been found to be solely dependent on the thickness of the cut through which the cutting stream passes (8).

Finally, it can be concluded from the literature search that temperature is the single most important parameter which could be used to monitor the cut quality.

5. EXPERIMENTAL SETUP

Two essential parts of the experimental setup necessary to perform this feasibility study were related to the setup of flame cutting equipment and that of the spectral radiance (temperature) and acoustic monitoring systems. The following subsections describe both setups in detail.

5.1 Cutting Torch Setup

A separate area of the Welding Research and Development laboratory was chosen to set up the cutting equipment furnished by the Victor Equipment Company of Denton, Texas. This laboratory area was suitable to provide the setup required for the instrumentation as well as the cutting operations. A view of the setup is shown in Figure 5-1. A special cutting table was built to allow water cooling of the plate and to secure the carriage track assembly. The equipment provided by Victor included the track and carriage assembly, four torches (two special short beveling torches), a variety of machine cutting tips (high preheat, high speed, and general purpose tips). Also provided was a series of flow meters with separate gauges and solenoid valves for the bevel cutting studies. The cutting setup and the initial parameters for the studies were established through close consultation with Victor representatives Messrs. Roger Zwicker, Ben Jezek and Jack Minser. The Victor standard cutting chart parameters were used as a reference to establish the settings for the various types and sizes of tips. The experimental setup allowed single torch perpendicular and bevel cutting as well as triple torch cutting of armor plate material. Appendix B describes a few specific problems encountered with the cutting apparatus and with development of the cutting technique.

The criteria used to determine or grade the quality of cuts included:

(1) Smooth finished plate surfaces

(2) Clean and square edges free of slag deposits

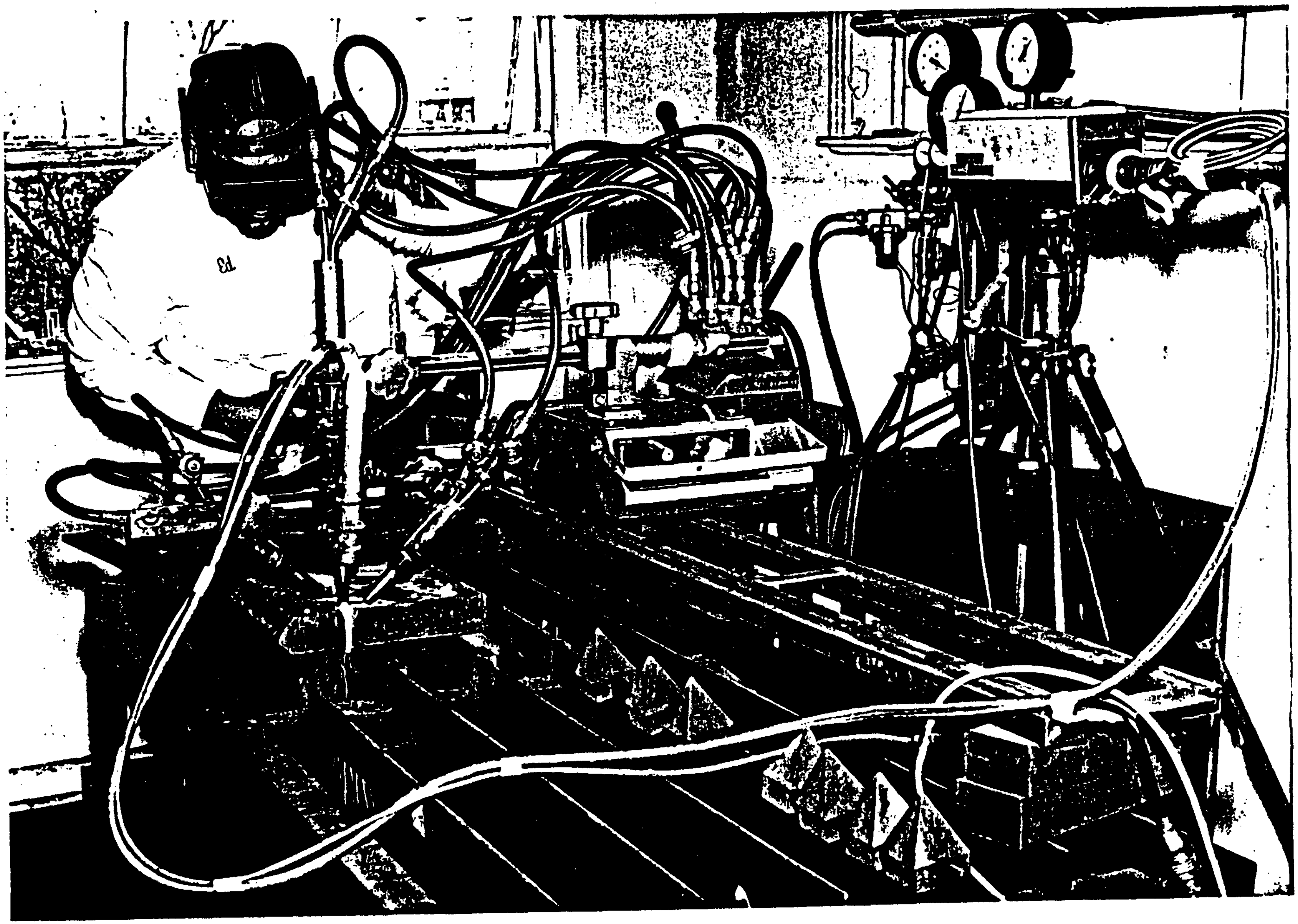


FIGURE 5-1. A VIEW OF THE EXPERIMENTAL FLAME CUTTING OPERATION

Those cuts which exhibited any rough plate faces, gouging, pits, rounded edges, excessive dross or slag, too much drag or loss of cut were considered bad cuts; they would require conditioning or rework. The settings and conditions were established to produce poor quality cuts by varying and recording individual parameters as follows:

(1) When the travel speed is too fast, the top edge remains clean and square while considerable slag adheres to the bottom due to incomplete oxidation. Occasional gouges can be seen and pronounced draglines slant away from the direction of the cut.

(2) When the travel speed is too slow, the top edges are rough and uneven due to prolonged exposure to the flames. Considerable slag usually adheres to the bottom edge. Severe gouges are produced by the erratic wandering action of the high pressure oxygen stream.

(3) When the cutting oxygen pressure is too high, the top edge is uneven and dished out as the excessive pressure causes the oxygen stream to expand upon entering the plate. The sound of this cut is exceptionally loud.

(4) When the cutting oyxgen pressure is too low, the lower portion of the plate face is rough and somewhat gouged due to the oxygen stream lacking sufficient pressure to penetrate. Considerable slag adheres to the bottom edge.

(5) When too much preheat is used, the top edge of the plate shows a rounded appearance and is somewhat melted away by the excessive preheat flame. Beads of molten metal form on the top edge and considerable slag is produced due to the large amount of metal being melted away.

(6) When too little preheat is used, the top edge is slightly rounded and out-of-square. Occasional pits and gouges along with distinct draglines can be seen on the plate face.

(7) When the tip is too far from the plate, the top edge shows signs of being blown away similar to the effect of too much oxygen pressure.

(8) When the tip is too close to the plate, the preheat flames interrupt the cutting oxygen stream causing the upper portion to appear rough and uneven. Occasional gouges may appear on the face of the plate.

The first task was to make good quality straight cuts on various thicknesses (3/4, 1, 1-1/4, 1-1/2, and 2 inches) of armor plate using general purpose high speed machine cutting tips HPN, MTHN, and GPN (tips supplied by Victor Equipment Company). No difficulty was encountered on the perpendicular cuts in armor plates (obtained from various manufacturers) versus carbon steel plates. The range of preheat, travel speeds and flow rates for quality cuts was found to be very wide.

In the second task, (single) bevel cutting parameters were established and recorded before attempts at triple bevel cutting were made. Various thicknesses were used to establish single bevel cutting parameters.

Several triple torch cuts were also made. Various parameters were used until good cuts could be produced. The greatest difficulty was in preheating for ignition, particularly for the third trailing torch.

The first attempt to initiate the trailing torch cuts was to pause the travel when each torch reached the starting edge of the plate. This technique was unsuccessful because the first and second torches gouged the plate during the pauses. The second approach was to use a hand-held preheating torch to preheat a localized region (where the second and third torches were to cut). On greater plate thicknesses (>2 inches) the hand-held preheat was necessary on both the top and bottom edges of the plate.

Variations of the parameters, developed for good triple torch cuts, were tried. Considerable variations apparently can be made without changing the quality of cut.

5.2 Flame Cut Monitoring Setup

The experimental setup for evaluation of parameters related to the quality of cut in flame cutting of armor plate was designed to provide a record of the visible and audible conditions for a range of cut quality. The visible and audible recording was made by a video tape and camera system while an acoustic emission system was used for recording high frequency acoustic noise. The instrumentation used for these experimental measurements is illustrated schematically in Figure 5-2. The cut quality was changed by varying the speed, cutting oxygen, or preheat over a wide range, sufficient to produce poor quality cuts at the extremes. The parameter evaluation was carried out on single torch perpendicular cuts. The selected parameters were verified on bevel as well as triple torch cuts.

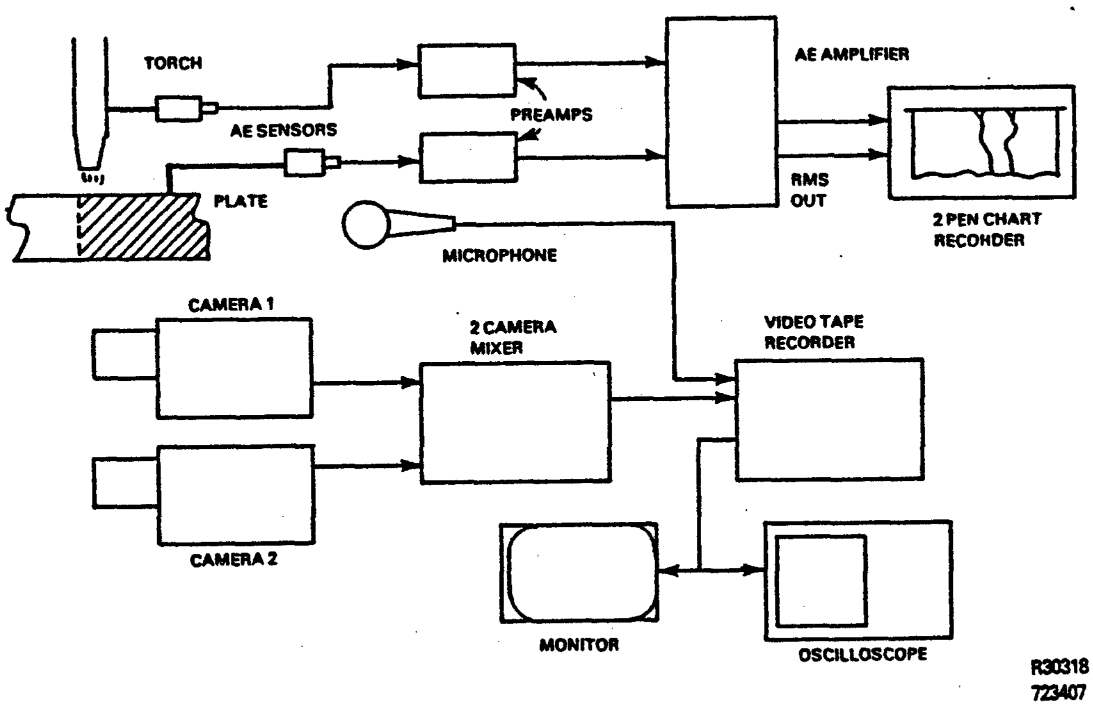


FIGURE 5-2. BLOCK DIAGRAM OF INSTRUMENTATION USED TO MONITOR FLAME CUTTING PROCESS

5.2.1 Spectral Radiance Monitor

In order to record spectral radiance (a variable which could be related to the temperature of the molten metal at the cutting front during flame cutting), a Wratten #70 filter was placed in front of the video camera lens. This limited the wavelength interval viewed by the camera lens to between 0.68 and 1.0 microns. In this wavelength range, a one percent temperature change will cause a 10-20 percent change in the spectral radiance.

The relative spectral radiance is related to the temperature and the recorded data by the following equation (13).

$$T_1 = \frac{1}{\frac{1}{T_0} - \frac{\lambda}{C_2} \ln \frac{V_1}{V_0}} \qquad (1)$$

where,

T_0 = reference temperature
V_0 = voltage from "line grabber" at reference point
V_1 = voltage at measured point
T_1 = temperature at measured point
λ = 0.84×10^{-6} m (center of filter range)
C_2 = a radiation constant

Section 7 provides details of the derivations for Equation 1.

The video tape containing spectral radiance data was analyzed quantitatively using a "line grabber" technique to convert selected horizontal scan lines of the video image into quantitative plots of the relative spectral radiance at various positions through the cutting front. The relative spectral radiance monitoring system was implemented in four different configurations in order to determine the optimum arrangement to monitor cut quality and is described as follows.

(1) Stationary Camera

A stationary camera set-up as illustrated in Figure 5-3 was evaluated using a 20-90 mm zoom lens. The lens was adjusted to view the full length of the cut. This arrangement was unsatisfactory because the distance from lens to cutting front changed and the position of the cutting front image on the video tape recorder (VTR) frame moved from bottom to top of the video frame as the cut was made. These variables introduced errors into the evaluation of relative spectral radiance data.

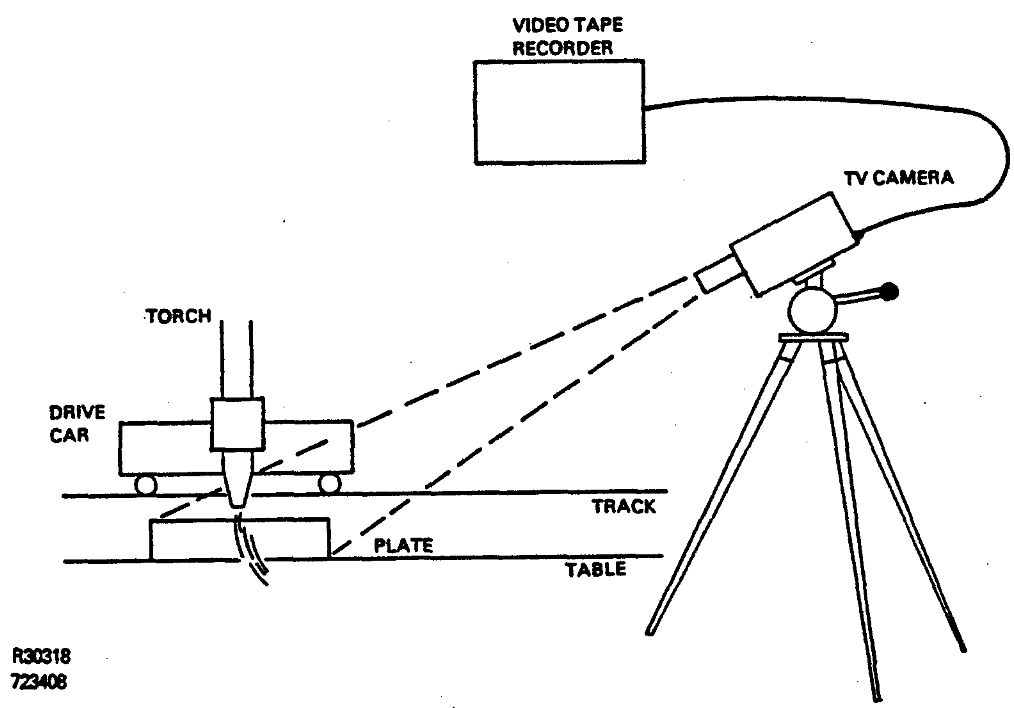


FIGURE 5-3. STATIONARY CAMERA USED TO RECORD THE MOVING CUTTING FRONT AND SHOW THE FULL LENGTH OF THE CUT

(2) Trailer-Mounted Camera

The video camera was made stationary with respect to the cutting front by mounting the camera on a trailer behind the cutting torch drive car. In order to position the camer to view the cutting front through a minimum length of the kerf, it was necessary to mount the camera 20-30 inches above and behind the cutting torch, as shown in Figure 5-4. This arrangement was very sensitive to vibration of the drive car and irregularities of the drive car track. The image jitter was unsatisfactory.

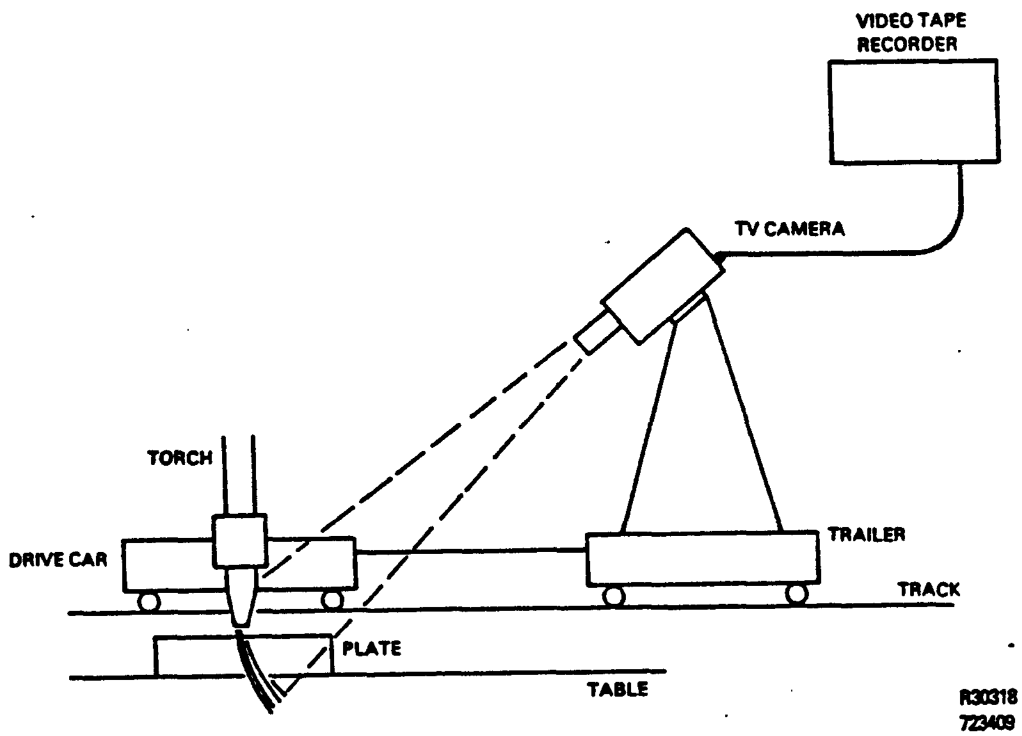


FIGURE 5-4. TV CAMERA ARRANGEMENT FOR DIRECT VIEW OF FLAME CUT THROUGH THE KERF. The image of the cutting front was stationary as the cut progressed.

(3) Camera and Mirror Setup

A satisfactory arrangement was found in the use of a mirror mounted on the torch drive car to direct the view of the video camera into the kerf from a steep angle while the camera was mounted low on the trailer (see Figure 5-5). The steep viewing angle provided a clear view of the cutting front and the low mounting of the camera provided a steady image at a fixed position on the video monitor. This setup was used for data recording on single torch, perpendicular cuts.

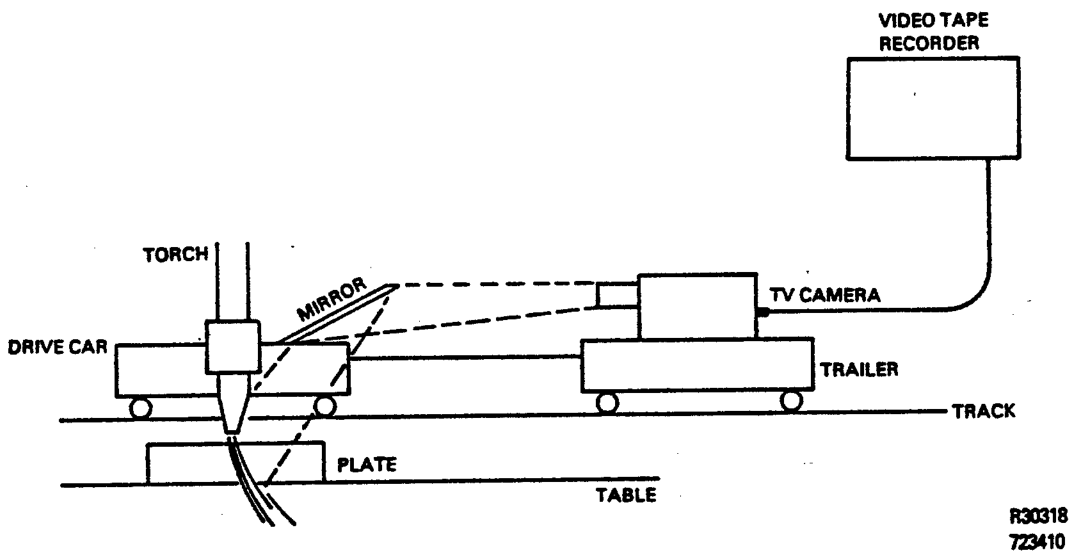


FIGURE 5-5. TV CAMERA ARRANGEMENT TO ACHIEVE A STEEPER VIEWING ANGLE INTO THE KERF AND ELIMINATE THE VIBRATION PROBLEM

(4) <u>Camera and Fiber Optic Setup</u>

The camera-mirror arrangement was unsatisfactory for bevel cutting because the mirror would not follow when the bevel cut angle was changed. A fiber optic device was attached to the camera in place of the zoom lens and attached to the cutting torch, as shown in Figure 5-6. In addition, the fiber optic objective lens was small enough that multiple torches could be instrumented individually when the triple torch evaluation was performed.

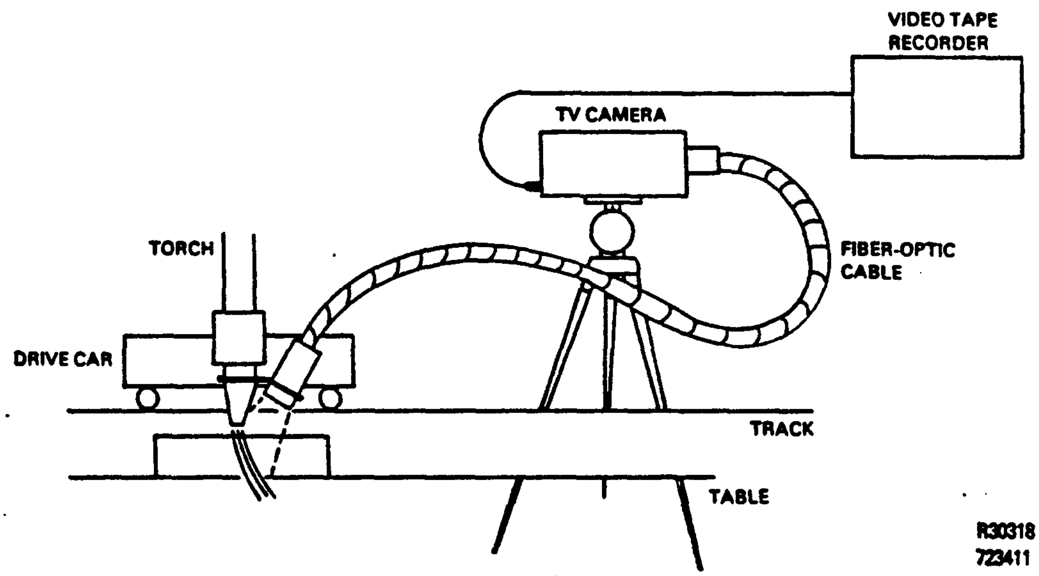


FIGURE 5-6. FIBER OPTIC CABLES USED TO INSTRUMENT MULTIPLE TORCH CUTTING SETUP. The fiber optic objective lenses were attached to the torches.

5.3 Acoustic Monitor

A cutting torch operator uses both visible and audible clues to adjust the torch for quality cutting. Therefore, the noise made by the cutting process was recorded at three points in order to evaluate the possibility of using the noise as a parameter for automatic control of flame cutting quality. The setup for the acoustic monitors is shown schematically in Figure 5-7.

5.3.1 Clamp-on AE Sensors

The sound of the gases flowing in the torch and the sound of the cutting process in the plate were monitored by high temperature acoustic emission (AE) sensors and the root mean squared (RMS) amplitude was recorded on a strip chart using an RMS converter.

An AE sensor was attached to the torch using a clamp-on acoustic waveguide assembly. A preamplifier of 40 dB gain in a frequency

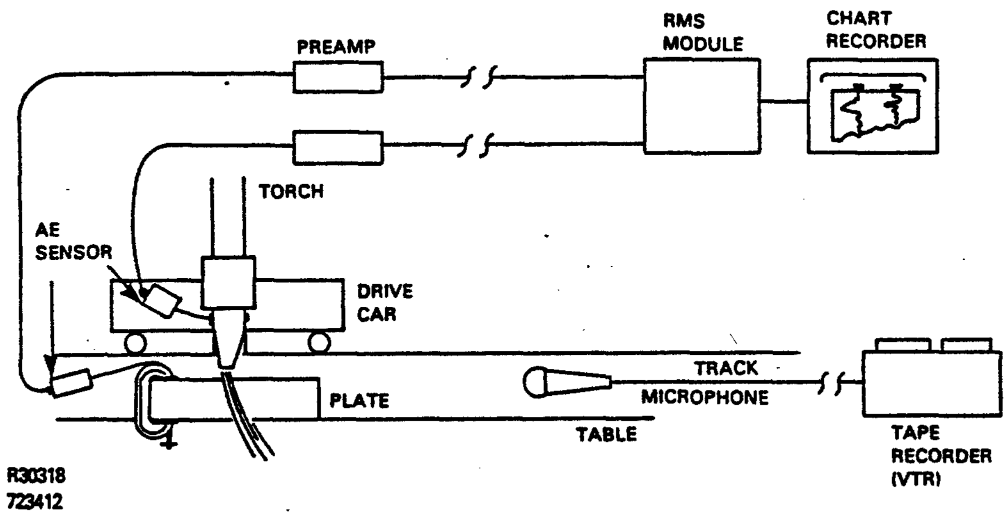


FIGURE 5-7. ACOUSTIC EMISSION SENSORS MOUNTED ON TORCH AND PLATE USED TO MONITOR CHANGES IN CHARACTERISTIC SOUND AS CUT PROGRESSED. A microphone near the plate was used to record airborne noise on the VTR sound track.

range of 50 kHz to 1.0 MHz was used to condition the signal before connection to the RMS converter. This sensor was used to evaluate the sensitivity of high frequency acoustic noise to changes in the flow of gases in the torch due to tip damage.

Another clamp-on AE sensor was mounted on the plate to evaluate the relation between high frequency acoustic noise and degradation of cut quality. A preamplifier of 40 dB gain in a frequency range of 50 kHz to 1.0 MHz was used to condition the signal before connection to the RMS converter.

5.3.2 Microphone

A microphone mounted near the plate was used to record the flame cutting noise in the audible frequency range on the sound track of the VTR. The noise from the flame cutting operation was expected to provide intelligence related to cut quality or to the onset of degraded cut quality.

6. DATA ACQUISITION

Initial practice cuts were made using ordinary mild steel plate and this opportunity was taken to develop the data acquisition protocol for subsequent flame cutting on armor plate. The process of video tape recording the image of the cutting front for quantitative analysis and comparison with cut quality was developed at this time. The study of flame cutting parameters was carried out on perpendicular cuts in 1.5-inch thick armor plate. The results were verified on bevel cuts in 1.25-inch thick armor plate and confirmed on triple torch cuts in 2.5-inch thick armor plate. The raw data showing various cutting parameters and resulting cut quality are included in Appendix C.

6.1 Perpendicular Cuts

A total of 93 perpendicular cuts were made in 2-inch thick carbon steel plate and 1.5-inch thick armor plate. Armor plate from several different manufacturers was used. The cut pieces were identified and correlated with the cutting parameters. The video and acoustic data were cataloged for later analysis.

The procedure for data acquisition on perpendicular cuts was to start from cutting parameters which produced consistent high quality cuts and vary one parameter at a time until poor quality cuts were produced at both extremes of the variable parameters.

The variable parameters were cutting speed, cutting oxygen flow/pressure, and preheat input. The preheat fuel-oxygen mixture was varied on some cuts but the variable of interest was the heat input from the preheat flame. The tip-to-plate spacing was not considered a variable because this parameter is automatically controlled on the cutting machines in the Lima Plant.

The video tape recordings were reviewed and identified for later analysis by the "line grabber" technique. The sound track of the VTR was reviewed and the position of the microphone was varied in search of a suitable monitoring location. However, noises extraneous to the cutting process were found to seriously degrade the sound record. Strip chart records of the RMS amplitude of the acoustic noise were also identified for later correlation with the cut surface of the plate.

6.2 Bevel Cuts

A total of 61 bevel cuts were made in 1.25-inch and 1.5-inch thick armor plate in order to verify that the control parameters identified for perpendicular cuts would be effective on bevel cuts. A series of practice cuts were made in order to develop a technique for making quality bevel cuts. Then the cutting speed, cutting oxygen, preheat oxygen, and preheat fuel were varied to produce poor quality cuts at the extremes of each parameter.

The video camera system was changed for the bevel cutting because the mirror arrangement could not easily be directed to view into the bevel cut. Instead, the fiber optic arrangement was set up so that when the angle of the torch was adjusted the view into the bevel cut did not change.

A series of 14 bevel cuts in 1.25-inch thick armor plate were made with all parameters held constant except the cutting speed. Speed was varied from 4 inches/minute to 15 inches/minute. At 15 inches/minute, it was not possible to sustain the cutting flame and at 4 inches/minute, excess melting of the top surface occurred and intermittent gouging was observed. The preheat oxygen and the preheat fuel were varied individually in a series of 16 bevel cuts in order to verify that each parameter affected the temperature of the cutting front and that the cut quality was affected in a similar way.

The bevel cut data were recorded on video tape for later analysis. The records of cutting parameters were identified with each numbered cut piece. Particular attention was given to identification of the finished side of each cut.

6.3 Triple Torch Cuts

Triple torch cuts were made to verify the transferability of the temperature parameter for process control to govern the quality of cut. A series of practice cuts were made and a total of 10 triple torch, double bevel and land (three-surface) cuts were made with high quality cut surfaces.

The setup for triple torch cuts required that all three cuts be recorded simultaneously on the video tape recorder. Initially, three fiber optic cameras were set up but the proximity of the fiber optic objective lenses to the surface of the plate allowed the reflected preheat flame to contact the glass filter holders. This excess heat destroyed the filters. The camera setup was changed to the earlier configuration of a stationary camera positioned at the end of the cutting table and arranged to look directly into the vertical kerf while the two bevel kerfs were viewed at an angle. As the triple torch cuts were required for verification only, this setup was satisfactory.

The triple torch cuts were difficult to control in the small plate specimens used for this series of tests. Lacking the heat sink of a large plate, heat buildup was a problem. Since the cut was started from an edge, it was necessary to use auxiliary preheat to raise the edge of the plate to kindling temperature for each torch. Considering the extraordinary conditions, it was fruitless to attempt to make a complete set of variable parameter cuts. Sufficient quality cuts were made, however, to ensure that the temperature in the kerf was the primary dependent variable.

The triple torch cuts were monitored by the video camera system with a zoom lens arranged so that the full length of the specimen was contained within the video frame. The cutting parameters were identified with each cut number so that the data could be correlated with the video records.

7. DATA ANALYSIS

Radiometric measurements of the flame cutting process were made using a television camera and a video tape recorder. A "line grabber" technique was used to make quantitative measurements from the recorded video images. The primary interest was in observation of changes in the temperature of the cutting front as cut quality was varied. Therefore, relative measurements were made by keeping all variables constant except surface temperature.

The spectral radiance $L\lambda$, in $W/m^2 \cdot ster$, at wavelength λ from a surface at temperature T in the interval λ_i is given by:

$$L_\lambda = \frac{C_1 \cdot E \cdot \lambda_i}{\lambda^5 \left(e^{C_2/\lambda T}\right) 2\Pi \text{ steradian}} \tag{2}$$

where:

$C_1 = 3.74 \times 10^{16}$, $W \cdot M^2$;
$C_2 = 1.4384 \times 10^2$, $M \cdot {}^\circ K$;
λ = wavelength (less than 1 micrometer)
λ_i = wavelength interval
T = temperature °K (less than 3000°K)
E = emissivity of surface

For the present case, the optical power impinging on a pixel in the television vidicon detector depends on distance to the source, lens parameters, and the size of the pixel. The optical power P impinging on a pixel is given by:

$$P = L_\lambda \cdot p \cdot \frac{I}{D} \cdot \left(\frac{f}{2F}\right)^2 \cdot \Pi \cdot \frac{1}{D^2} \cdot K \tag{3}$$

where:

λ = wavelength

p = area of a pixel

I = image to lens distance

D = object to lens distance

f = focal length of lens

F = focal length of aperture

K = optical filter transmission

The vidicon detector converts optical power to voltage and the camera-VTR roster scanning system stores an analog of the voltage on the video tape. The "line grabber" technique is a means to recover and make quantitative measurements on the recorded data. Figure 7-1 illustrates the data reduction process.

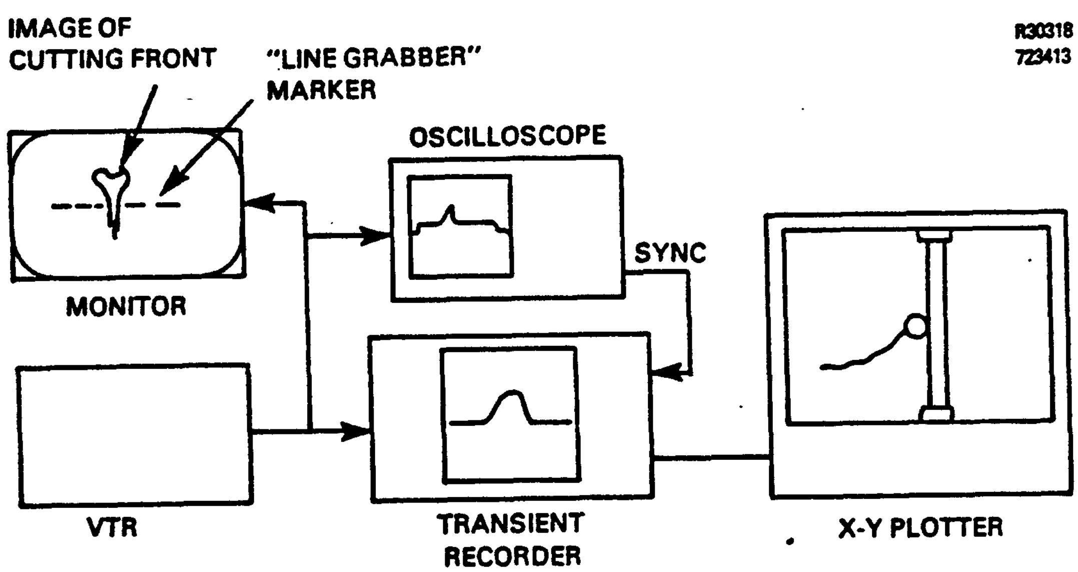


FIGURE 7-1. ILLUSTRATION OF THE METHOD USED FOR DATA REDUCTION AND ANALYSIS. The recorded images of flame cuts were broken down into horizontal scan lines which were displayed on an X-Y plot for analysis of radiant intensity vs. cut quality.

The reproduced voltage from this system is given by:

$$V = P \cdot S \cdot G \cdot R \tag{4}$$

where:

V = voltage out

S = sensitivity of vidicon

G = voltage gain of camera

R = record-reproduce gain of VTR

Calibration of this record-reproduce system for absolute temperature measurements would be a tedious process. We chose to keep all variables constant and perform data analysis on a relative basis to determine the effect on the spectral radiance of the cutting surface due to conditions leading to poor quality cuts.

Taking the ratio of voltage output, Equations 2, 3, and 4 reduce to:

$$T_1 = \frac{1}{\frac{1}{T_0} - \frac{\lambda}{C_2} \ln \frac{V_1}{V_0}} \tag{5}$$

7.1 Video Tape Review

The recorded data on video tape were transferred to chart form using the "line grabber" technique. The cutting parameter data, the video image and the "line grabber" presentation were reviewed for each cut and a sequence of scans was transferred to chart form for each parametric variable series; i.e., cutting speed, cutting oxygen, and preheat flame.

7.2 Spectral Radiance Charts

Nine scans were charted for each cut, as illustrated in Figure 7-2. Three vertical slices (top of kerf, middle of kerf and bottom of kerf) were taken at the beginning of cut, middle of cut and end of cut to provide a presentation of spectral radiance data for each cut. An example of the charted data is shown in Figure 7-3, which also illustrates the dramatic effect of cutting at too slow a cutting speed. Typical charted data for perpendicular, bevel and triple-torch cuts are included in Appendix D.

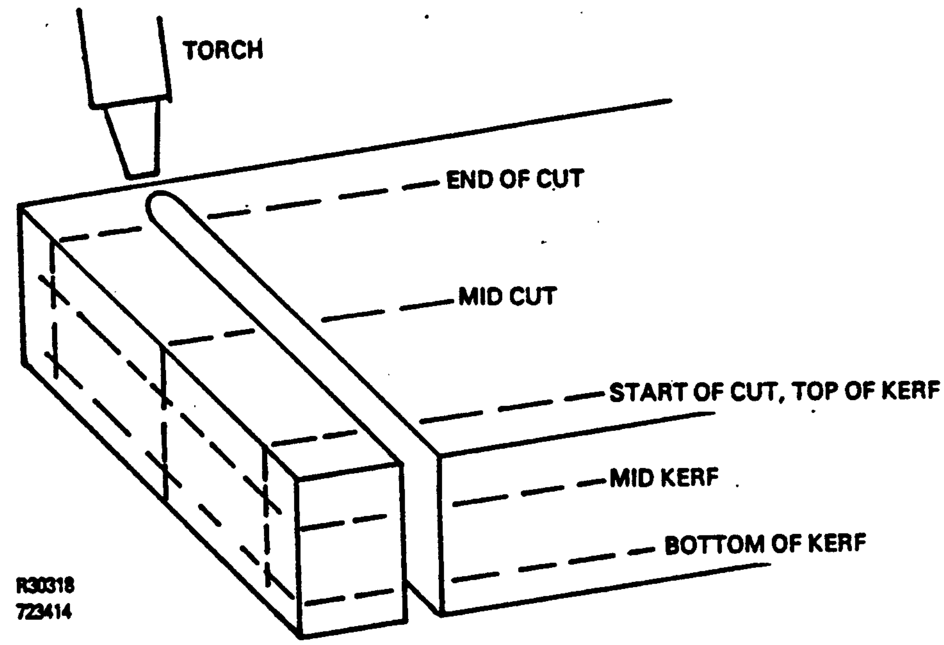


FIGURE 7-2. ILLUSTRATION OF THE NINE POSITIONS ON THE PLATE SELECTED FOR DATA REDUCTION. Three vertical slices were taken at three points along the cut.

The spectral radiance charts from the top of the kerf were taken on a line crossing the kerf directly beneath the torch tip. Thus, the direct effect of preheat input could be observed on either side of the kerf (for bevel cuts, the waste side of the cut was ignored). The temperature in this region increased when cutting speed was too slow or when the preheat flame was too intense. Figure 7-4 shows the change of relative spectral radiance at the shoulder of the kerf as a function of preheat input.

The spectral radiance from the mid-kerf region responded slightly to both preheat and cutting oxygen changes but was less responsive than from the top and bottom of the kerf, as shown in Figure 7-3.

The spectral radiance from the bottom of the kerf responded dramatically to change of cutting speed, as shown in Figure 7-5. The effect of cutting speed on relative spectral radiance is shown in Figure 7-6, which was plotted from the peak value of the bottom of kerf charts. The bottom of kerf peak value also reflects changes in cutting oxygen flow, as shown in Figure 7-7.

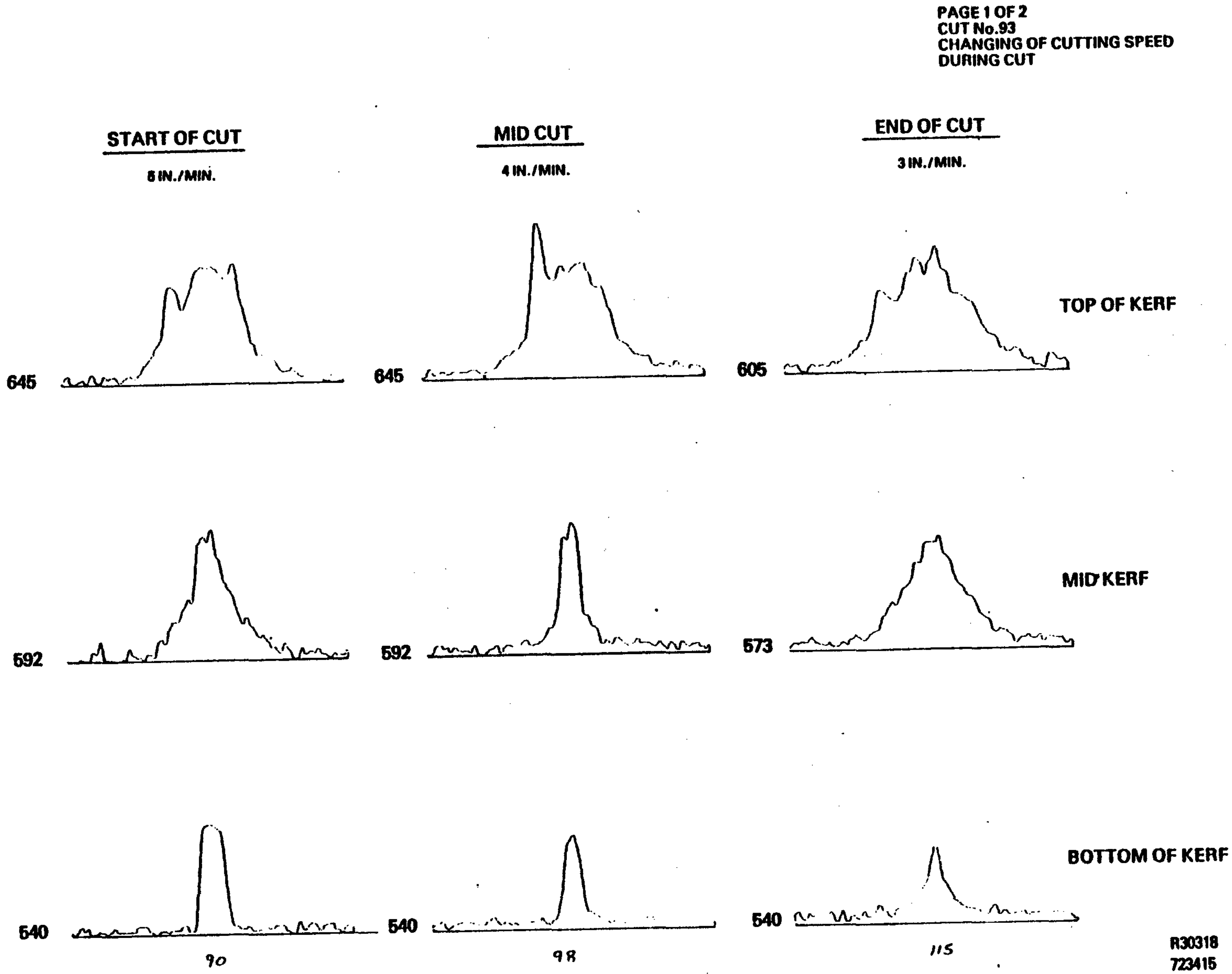


FIGURE 7-3. EXAMPLE OF CHARTED RELATIVE SPECTRAL RADIANCE FROM A FLAME CUT IN 1-1/2 INCH ARMOR PLATE. The effect of changing cutting speed is dramatically illustrated by slices from the bottom of the kerf.

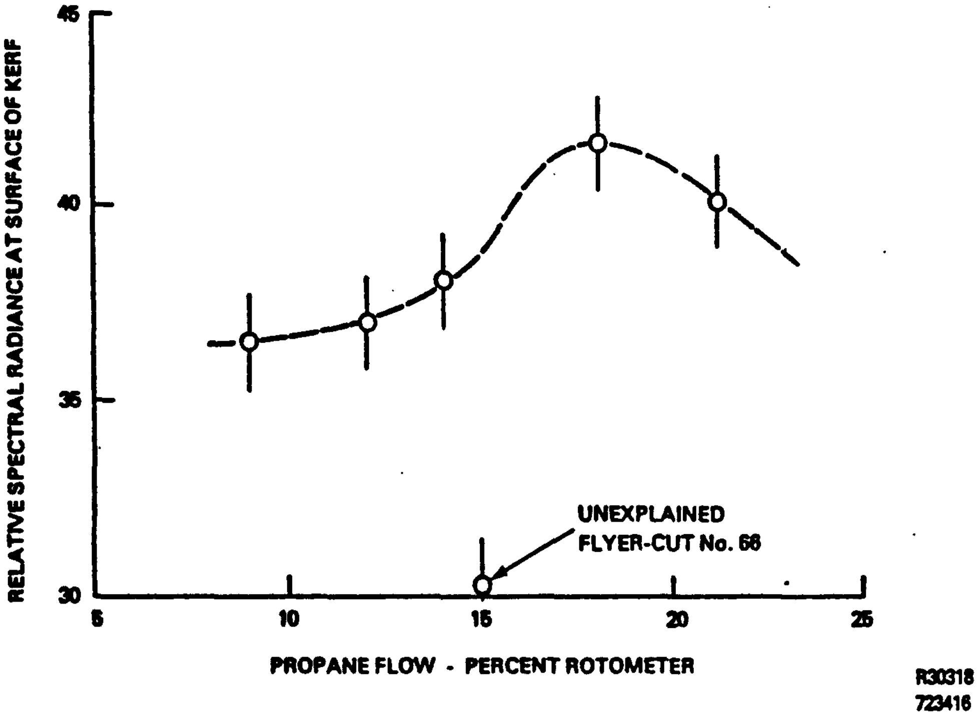


FIGURE 7-4. CHANGE OF RELATIVE SPECTRAL RADIANCE AS A FUNCTION OF PREHEAT INPUT FOR PERPENDICULAR SINGLE TORCH CUTS IN 1.5-INCH ARM PLATE. Preheat oxygen was adjusted for the proper mixture at each propane flow.

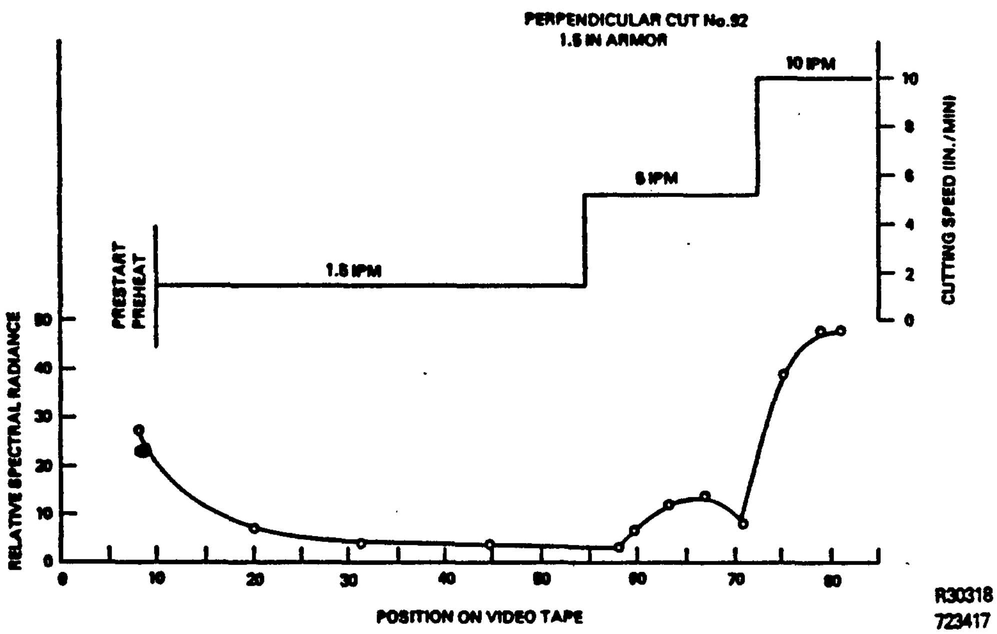


FIGURE 7-5. RELATION OF CUTTING SPEED TO RELATIVE SPECTRAL RESPONSE FOR PERPENDICULAR SINGLE TORCH CUTS IN 1.5-INCH ARMOR PLATE

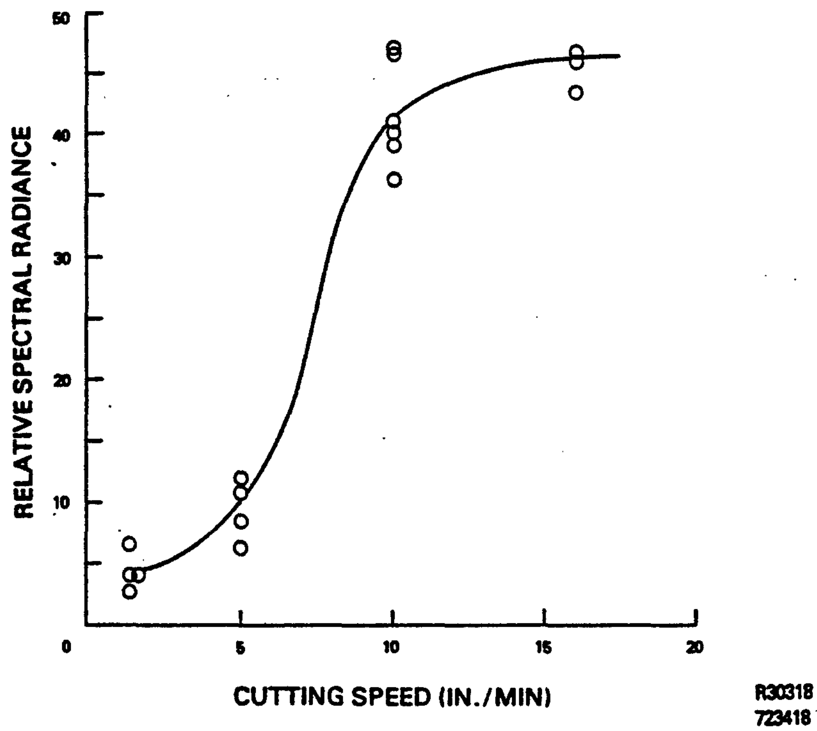


FIGURE 7-6. EFFECT OF CUTTING SPEED ON RELATIVE SPECTRAL RADIANCE FOR PERPENDICULAR SINGLE TORCH CUTS IN 1.5-INCH ARMOR PLATE

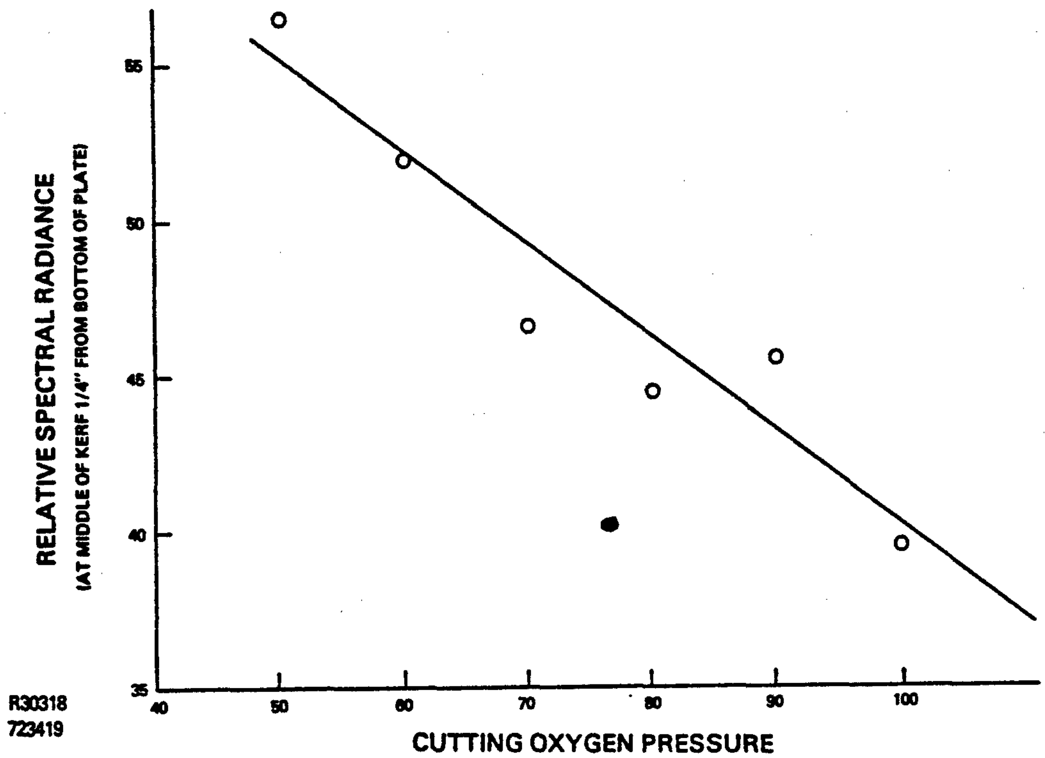


FIGURE 7-7. CHANGE IN RELATIVE SPECTRAL RADIANCE AS A FUNCTION OF CUTTING OXYGEN PRESSURE

8. DISCUSSION OF RESULTS

The experimental flame cutting of armor plate was performed in order to determine the feasibility of an automatic cutting process control. The cutting parameters speed, oxygen and preheat were varied to produce a range of cut quality. The relative spectral radiance from the kerf was recorded on a video tape recorder and the RMS noise amplitude in both the plate and the torch assembly was recorded on a strip chart. Correlation of these data led to the selection of kerf temperature (represented by spectral radiance) as the most effective dependent variable.

8.1 Selection of Control Parameters

The spectral radiance of the kerf is a very sensitive indicator of kerf temperature. The relative spectral radiance measurements made for this study show that the temperature of the kerf changed in a predictable way as the cutting parameters were varied (see Section 7). Further, the spectral radiance measured at the kerf shoulder and near the bottom of the kerf at the cutting front indicated in advance the degradation of cut quality. A simple logic sequence (shown in Figure 8-1) was developed to determine the cutting parameter which required correction.

The cutting oxygen and cutting speed both were found to affect the spectral radiance at the bottom of the cutting front, but the cutting speed and preheat affected the spectral radiance at the kerf shoulder. Therefore, taken together the parameters were resolvable, as shown in Figure 8-2.

Figure 8-3 shows a schematic closed loop real-time process control system concept. In this control system, error signals from temperature sensors are processed to develop corrective control signals to the cutting torch. The action to be taken for each measurement condition is shown in Table 8-1.

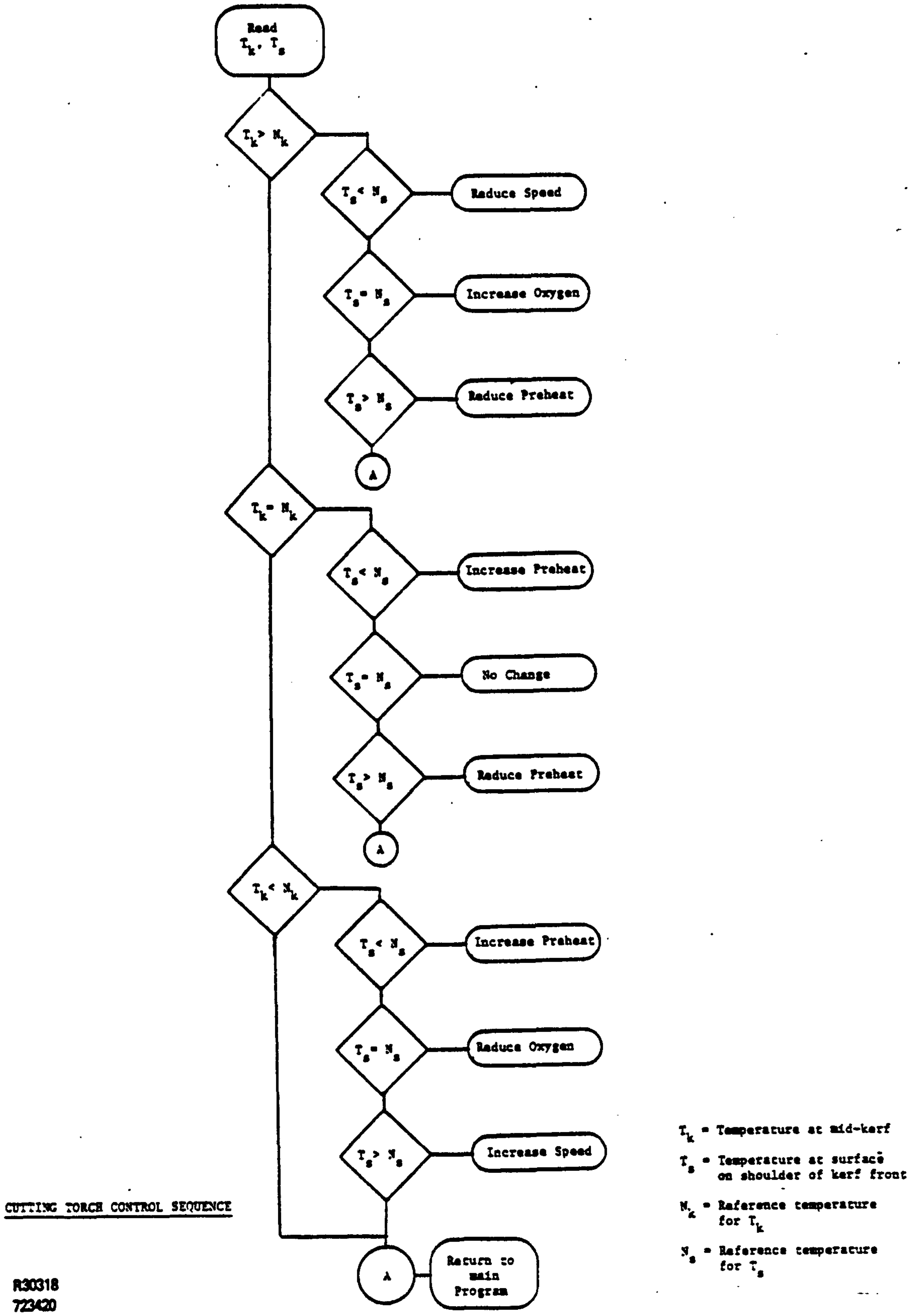


FIGURE 8-1. CUTTING TORCH CONTROL SEQUENCE

MID KERF TEMPERATURE (T_k)

KERF SHOULDER TEMPERATURE (T_s)	HIGH	NORMAL	LOW
HIGH	TOO MUCH PREHEAT AND/OR CUTTING OXYGEN TOO LOW	TOO MUCH PREHEAT	TOO SLOW
NORMAL	CUTTING OXYGEN TOO LOW	NORMAL	CUTTING OXYGEN TOO HIGH
LOW	TOO FAST	TOO LITTLE PREHEAT	TOO LITTLE PREHEAT AND/OR CUTTING OXYGEN TOO HIGH

R30318
723421

FIGURE 8-2. RELATION OF THE MEASURED PARAMETERS (T_k, T_s) TO THE THREE VARIABLES WHICH AFFECT CUT QUALITY (CUTTING SPEED, PREHEAT INTENSITY, AND CUTTING OXYGEN FLOW RATE)

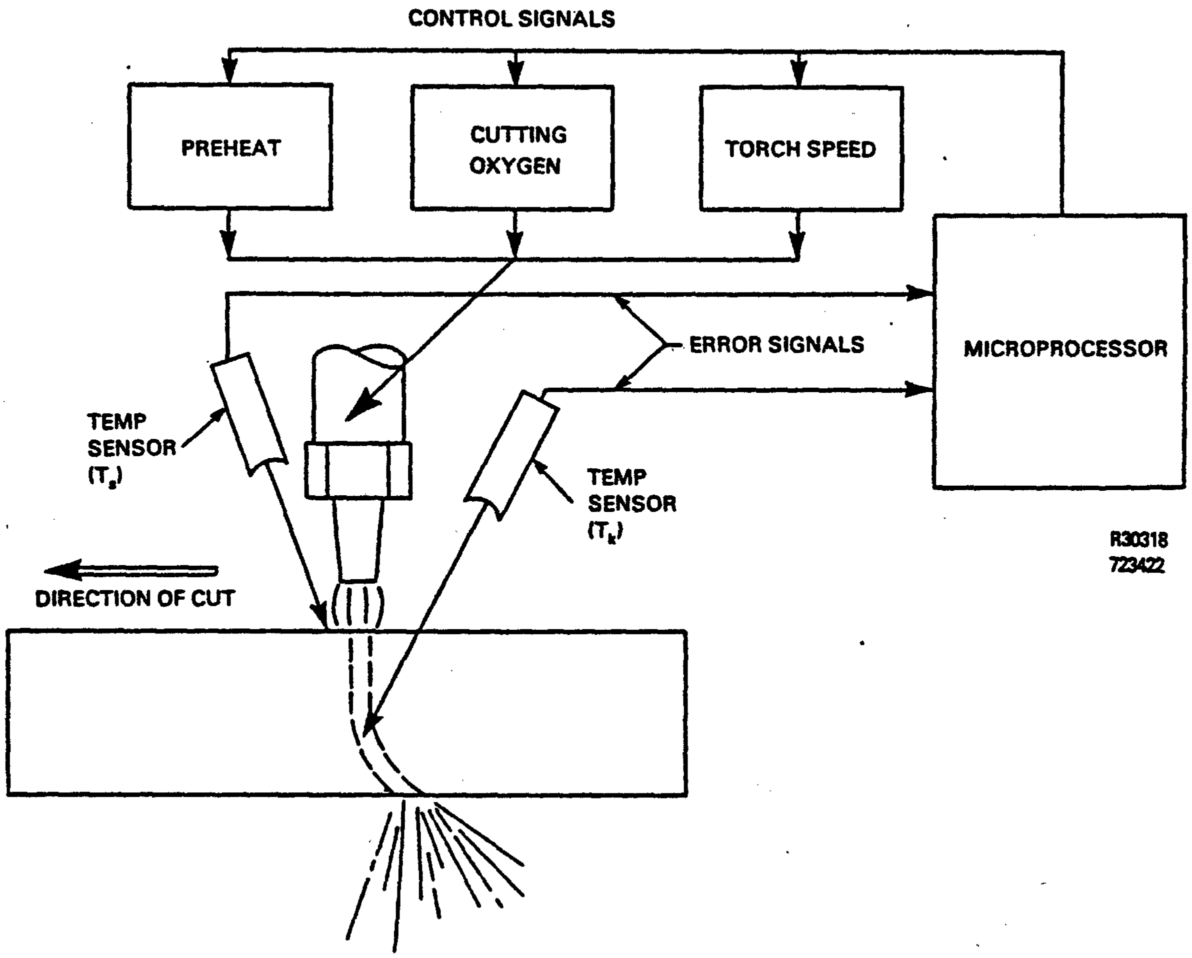


FIGURE 8-3. SCHEMATIC OF THE CLOSED-LOOP CONTROL SYSTEM CONCEPT

TABLE 1. CONTROL SCHEME

Condition	Response
T_k = hi & T_s = lo	Reduce speed
T_k = ok & T_s = lo	Increase preheat
T_k = hi & T_s = ok	Increase cutting oxygen
T_k = ok & T_s = hi	Reduce preheat
T_k = lo & T_s = hi	Increase speed
T_k = lo & T_s = ok	Reduce O_2 (cutting)
T_k = hi & T_s = hi	Reduce preheat, increase O_2 (cutting)
T_k = lo & T_s = lo	Increase preheat, reduce O_2 (cutting)
T_k = ok & T_s = ok	No change

- T_k = temperature at mid-kerf
- T_s = temperature at surface on shoulder of kerf front

The AE sensor attached to the torch tip was found to reflect changes in flow condition in the tip. Spatter of molten metal and other causes of damage to the torch tip could be detected with that sensor.

The AE sensor mounted on the plate indicated the presence of adhering slag and the occurrence of gouging. But because these conditions were indicated after the fact, the AE response was not selected as a process control parameter.

The airborne noise from the cutting process was also recorded during cutting, but many extraneous noises such as machines and motors were also recorded and these noises masked changes in the cutting process noise.

8.2 Bevel Cut Verification

A series of 61 bevel cuts were made to verify that the temperature of the cutting front was a suitable process control parameter. It was found that spectral radiance varied with cut quality, as with the perpendicular cuts. This is illustrated in Figure 8-4, which shows the effect of cutting speed on the spectral radiance.

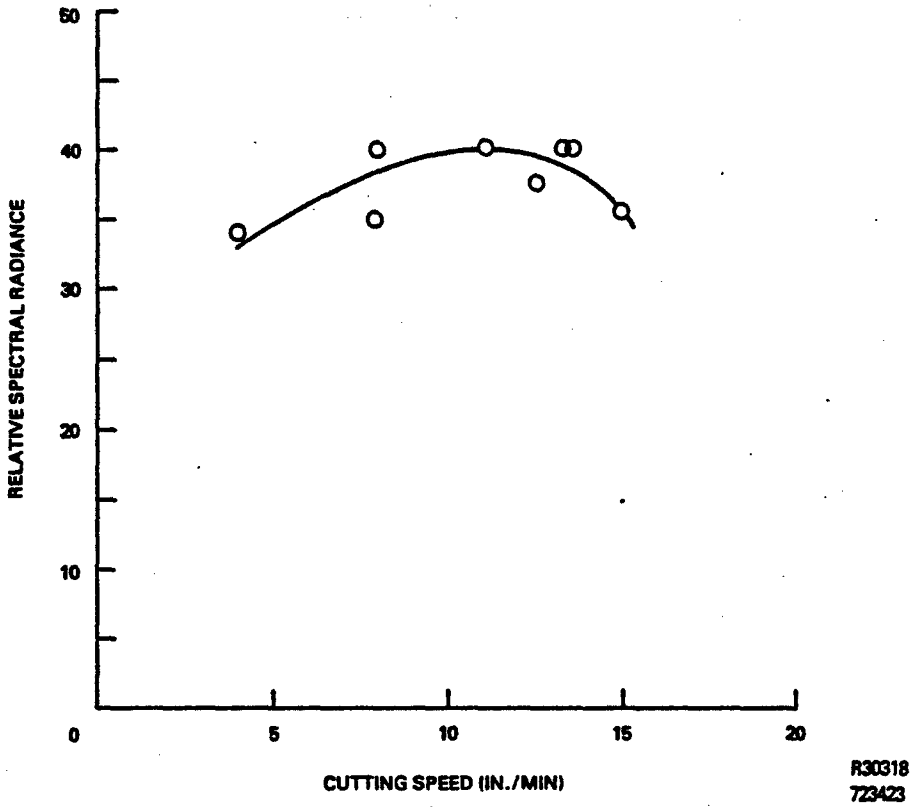


FIGURE 8-4. EFFECT OF CUTTING SPEED ON RELATIVE SPECTRAL RADIANCE FOR LEVEL CUTS IN 1.5-INCH ARMOR PLATE

8.3 Triple Torch Verification

A series of triple torch cuts were made in armor plate to verify that the cutting front temperature was a dependent variable, even though heat input was from three separate sources. Comparison of the spectral radiance charts from the triple torch cuts indicated that a similar relation existed between cutting front temperature and cut quality. Use of small plate specimens precluded development of a series of cuts with a parametric variation, as was done with perpendicular cuts. With input from three torches, the heat buildup in the plate was excessive.

9. CONCLUSIONS AND RECOMMENDATIONS

The feasibility study to evaluate the oxyfuel gas cutting process, through experimental data and literature search, has shown that flame-cut quality depends upon the temperature of the metal at the cut and the proper combustion mixture of oxygen and metal. These two conditions are interactive because both the torch travel speed and the cutting oxygen affect the metal temperature and the oxygen-metal mixture. The preheat flame, however, primarily affects the metal temperature and provides kindling temperature for cut initiation. Since the speed, cutting oxygen, and preheat interact and have overlapping effects, it was necessary to identify variables which could be used to sort out the cutting parameters and determine which should be adjusted when cut quality began to deteriorate.

The feasibility study has shown that the quality of cut could be controlled by monitoring the metal temperature at two points on the kerf: first, the shoulder of the kerf inside the preheat flame impingement zone, and second, the lower half of the kerf at the cutting front. The experimental data has also shown that the material thickness and chemical composition of plates (i.e., fabricated by different manufacturers) do not affect the temperature control parameters in any significant way.

The feasibility study has also demonstrated that high frequency acoustic sensors could be used to detect abnormal tip/torch conditions as well as flame cutting conditions.

A real-time closed loop system has been described in this report. It is highly recommended that such a closed loop proof test model be developed and tested; and, after a successful demonstration of the proof test model, that a prototype model be manufactured, and evaluated at the Lima Army Tank Plant before making production models and installing them on all the cutting machines at the Lima Plant.

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APPENDIX A

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APPENDIX A

BIBLIOGRAPHY

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APPENDIX B

EQUIPMENT AND CUTTING TECHNIQUE DEVELOPMENT

APPENDIX B

EQUIPMENT AND CUTTING TECHNIQUE DEVELOPMENT

Equipment Development

(1) The track assembly for the cutting machine carriage was too flexible for the experimental setup. The track was reinforced by tack welding 1" x 1-3/4" x 72" steel bars for stiffening. In the initial testing the track was also used as a tracking cart for the TV camera. This was later eliminated in favor of remote viewing to protect the lenses and equipment.

(2) The carriage had to be counter-weighted and caused some tipping of the torches at times. The machine carriage speed control dial was not marked in fine enough increments to determine accurate speeds. A stop watch and travel distance measurement were necessary to determine travel speed for each setup.

(3) The cutting torch-rack and positioning assembly for bevel cutting was found to be inadequate for accurate setups. Both the rack gear for height control and a protractor measuring device for angularity of individual torches were lacking. This hindered the repeatability and dimensional accuracy of the resulting bevels that might be necessary.

Because of inadequate torch positioning devices, it was very difficult and time-consuming to establish accurate torch-to-work standoff distance.

(4) Cutting table supports for leveling of plate specimens was critical and some cutting table modifications were necessary. Removable bars and pyramid supports were installed.

(5) Actual flow rates for cutting oxygen for the larger tips (Nos. 3, 4, and 5) were not measurable on the flow meter provided. For future work, a larger volume flow meter will be necessary.

Cutting Technique Development

(1) Cutting parameters (i.e. preheat, cutting, oxygen and travel speed) were found to cover a wide range of variability using a proper sized tip. This was quite prominent for straight cuts. Gouging, top edge melting and loss of cut were made only with extreme changes in parameters. This work on straight cuts was done primarily with MTHN tips (natural gas, machine, high preheat, and high speed tips).

(2) Bevel cuts were difficult to make for several reasons. The parameters affecting the quality of cuts included the leveling of the plate, the stand-off distance (maintaining), the tip size and the proper preheat. Much more preheat was needed for bevel cutting as compared to perpendicular cutting.

In making triple torch cuts, pausing of the travel to initiate the second and third torch cuts was unsuccessful because it caused gouging in the first torch cut. Triple torch cuts could not be started at the edge of the plates without using an additional hand torch for preheating. This preheating was required at both the top and bottom edges of the plate.

(3) The fiber optic sensors installed on the torch racks were a problem when adjustments in the torches were required. Sometimes the sensors had to be removed to make the necessary adjustments.

(4) Plate temperatures were maintained from cut to cut by water cooling. However, plate temperatures were not measured or recorded. Plate temperature was not considered to be a critical variable for this study.

APPENDIX C

RAW DATA SHOWING VARIOUS CUTTING PARAMETERS

7/16/82

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Visitor Visitors

Ben	Jezek								
Jack	Minser		Tip 2-MTH N						
Roger	Zwicker					400 SFH max			
Cut No	PH O2	Flow/press	PH Fuel	Flow/press	Cutting Oxygen	Flow/Press	Speed	Stand off	
1/ Good	Set 20 Flowing	19	pressure 20	11	91 psi 90 psi	66	Set 10 IPM Act 9 IPM	5/8-3/4"	
2/ Slow	24	19/25	24	11/23.75	90	66/108 Set	3 1/2	Gouges	
3/ Fast	24	19/25	24	11/24	90	66/108	16	Lost Cut halfway	
4/ Hi Preheat	24	61/24	24	35/22.5	90	66/108	10	1/8" Roll Over	
5/ Higher Preheat	60	68/96	30	48/39	90	66/108	10	1/4" Roll Over	
6/ Low Preheat	24	0/	24	0/	90	66/108	10	Lost Cut last 3/8"	
7/ Repeat Good	23	25/23	24	16/24	90	66/108	10		
			Tip 2-GPN						
8/ Good	23	25/23	24	16/24	90/90	33/108	5-5 1/2		
9/ Slow	23	25/23	24	16/24	90	33/108	2 1/2	Gouging	

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Signature: W R Schick

9/30/82

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2nd set of data — Cutting Parameter

GPS, WDJ, RLS
Ed R.

Tip No. — ~~2GPM~~ 2-MTHN
Tape No. — #2

Cut No	PH O_2 /	flow/pr.	PH fuel	flow/pr.	Cutting O_2	flow/pr.	speed	Standoff	Remarks
10/good	24	24/28	24	16/26.5	90	63/112	10	5/8"	ignore adj. going
11/good	24	24/28	24	16/26	90	64/113	10	5/8"	
12/good	24	23.5/28	24	15/25	90	63/112.5	10	5/8"	
13/Slow	24	18.75/28	23.75	11/24.5	90	64/113	??	5/8"	didn't cut all the way thru.
green filter ⇒ x #10 14/Slow	24	19.5/27.5	22	11.75/22.25	90	64/112	≃5	5/8"	Good cut
15/Slow	24	19/27.5	24	11/31	90	64/112	≃5	5/16"	start changed to
16/fast	24	18.5/27.5	24	11/31	90	64/112	~~6~~16	5/8	

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Cut #	PH O_2	Flow/press	PH Fuel Press	Flow/Press	Cutting Oxygen	Flow/Press	Speed	Stand Off	
17	24	25.5	24	15/16	90 psi	62	10" ipm	5/8"	
18	24	25	24	13.	90	62	3" ipm.	3/4"	
19	24	23	24	11	90	62	3" ipm	5/8"	
20	24	27	24	19	96	62	3" ipm	5/8"	
21	24	25	24	13	97	66	3½ ipm	3/4"	
22	24	22.5	24	11	88	62	2¼ ipm	5/8"	Gouge
23	24	22.5	24	11	88	62	2¼ ipm	5/8"	Gouged 3 places
24	24	23	24	16	90	33	2¼ ipm	5/8"	
25	24	19	24	11	90	62	2¼ ipm	3/4"	
26	24	19	24	11	90	62	1½" ipm	5/8"	Gouged
27	24	19	24	11	90	62	1½ ipm	5/8"	Gouged
28	24	19	24	11	90	62	1½ ipm	5/8"	Gouged
29	24	25	24	15	90	62	10 ipm	5/8"	Good

Date:

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Cut #	PH O_2	Flow/press	PH Fuel Press.	Flow/Press	Cutting Oxygen	Flow/press	Speed	Stand Off	
30		235		17	61			5/32"	
31		68		39	61			5/8"	
32		30		20	61			1"	
33		35		22	61			1"	
34		45		22	61			1/2"	
35		67		39	61			3/8"	
36		68		475	61			1/4"	

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37	15-23-86							
38	13-17-54							
				16-15 Propane				
39	15-25-33							
				25-24 Oxy				
				33 Cutting Oxygen				
				10 ipm 5/8" gap				

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Armor Plate

#		Prop.	Oxy	Cut Oxy	I.P.M.	10-22-82 Gap			
42		15	24	54	10	5/8			
43		"	"	"	"	"			
44		16	25	33	1	"			
45		16	25	33	2	"			
46		same as	42						
47		13	17	54	10				
48		16	25	54		3/4"			
49		"	"	"		"			
50		"	"	"		"			
51		"	"	"		"			
52		16	25	60	1st inch 1	3/4"			
					2 3"				
				54	10		10-28-82		
53		24	23	90	10	5/8"		Good	
	15		25	64					
54	118	24	24	90	1½ ipm	5/8"	Bad	[illegible]	
			35	62					
55	11	24	25	62	1½ ipm	5/8	1st 2"		Bad
							Rest		
56						1st step started and notice	[illegible]	Ground Surf.	
57	8		20		10" 1½ ipm		5" Good 3 Bad	Ground ½ [illegible]	

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		CHANGE	I.P.M.	Series					
		PROP	OXY	CUTTING	IPM	G -			
58		15	25	64	10	5/8			
59		"	"		7	"	Armor Plate		
60		"		"	4	"			
61		"	"		1	"			
62		"	"	"	13	"			
63		"	"	"	16	"			
64		"	"	"	19	"			
65		"	"		22	"			
	CHANGE	CUTTING	PRESSURE		SERIES				
66		15	25	62 FLOW/PSI	10	5/8			
67		"	"	65/90	"	"			
68		"	"	70/99	"	"	Armor Plate		
69		"	"	60/82	"	"			
70		"	"	50/67	"	"			
71		"	"	40/51	"	"			
72		"	"	30/36	"	"			

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SOUTHWEST RESEARCH INSTITUTE Armor Plate 1/2"

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Gary's Cuts 11-1-82

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		Prop flow		Oxy. Heat		Cutting Flow	P.S.I 88	I.P.M	Stage
73		9		13.5		62		10	5/8
74		12		17		"		"	"
75		18		31		"		"	"
76		21		34		"		"	"
77		9		28		65		16	1/4"
78		14		26		64		10	"
79		"		"		"		5	"
80		"		"		52	70 PSI	16	
81		"		"		46	60 PSI	"	"
82		8		11		64	90 PSI	"	"
83		14		26		71	100 PSI	"	"
83		14		26		40	90 PSI	"	"
84		"		"		"		"	"
85								10	"
86		14		26		40		5	"

#2 MTH Tip

#1 MTH

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Armor Plate

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		Prop		Oxy		Cutting Flow	80 PSI	I.P.M.	Stand off
87		14.		26		36		16	1/4
							70 PSI		
88		14		26		33		"	1/4
							60 PSI		
89		"		"		29		"	"
							50 PSI		
90		"		"				"	"
							100 PSI		
91.		"		"		41		"	"
Gouged 92		"		"		41		1 1/2"	"
		After 3" of cutting ipm changed to 5 ipm							
		last 2" ipm was raised to 10 ipm							
93								5 ipm	
								4 "	
								3 "	
								3 1/2 "	
								4 "	
								3 1/2 "	

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Bevel Cut
Short torch
3HPN tip.
~~45° Bevel~~

Cuts By Jack

Cut #	PH fuel	PH O_2	Cutting O_2	Speed	Bevel ∢	Plate thickness	Res
B1	34/30	68/30	48/45	? 10	45°		Gougin
B2	47/36	93/36	48/44	12.8 10	45°		Excellen
B3	29/36	47/36	42/44	11.8 10	45°		gougin
B4	47/36	74/36	43/48	8.6 10	45°		gougin. (
B5	48 ~~34~~/36 (50)	94 ~~48~~/36 (74)	43/48	9.1 10	45°		3/4 good 1/4 lost g
B6	44/36	94/36	43/48	5 6.1	45°		Top roll good bo
B7	44/36	94/36	43/48	12.8 ~~15~~ 12 ≃ 13	45°		good a but had pry it ap (didn't d
B8	43/36	94/36	42/48	≃17 11.8	45°		(1) occasion ~~[illegible]~~ ~~[illegible]~~ gougin: lot of goug at end (2) dishin (3) dragline falling be
B9	43/36	94/36	64/60	≃17 14	45°	less pronounced than B8	(1) dragline fal behind
B10	43/36	94/36	67/74	≃17	45°		(2) (1) & (3) as in B8

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Tip 3-HPM

CUT #	PH O^2	FLOW PRESSURE	PH FUEL PRESSURE	FLOW PRESSURE	CUTTING OXYGEN	FLOW PRESSURE	TRAVEL	STAND-OFF	APPEARANCE
	% ind/Pr.		% ind/Pr.		% ind/Pr.				
B11	94/74	38	45/50.2	37	43/150	48	≃10	too much	1½" good rest gouged
B12	94/74	38	45/50.2	37	43/151	48	≃13	still too much	1¼" good rest gouged
B13	94/74	38	45/50.2	37	43/150	48	≃13	very close to the plate	excellent
B14	94/74	38	45/50.2	37	43	48	≃13	high	3" good rest gouged
B15	93/73.5	38	45/50.2	38	43/148.5	48	≃13	.025	gouged
B16	93/73.5	38	45/50.2	37	43/148.5	48	≃12	.025	gouged
B17	93/73.5	38	45/50.2	37	43/148.5	48	≃12	.025	gouged
B18	93/73	36	45/50.2	37	43/148.5	48	≃13	.025	gouged
B19	94/67	38	45/50	37	43/143	?	≃13	very small (.025	Bad
B20	58/68	38	25/50.75	37	67/142.5	76	≃12		reasonably good
B21	58/68	38	25/50.75	37	69/142.5	76	≃15		Bad
B22	50/68	38	25/50.5	38	67		≃12.8		good
B23	51/68	38	25/50.5	38	68/143	76	≃12		Partly gouged

Date:

Signature:

(SwR 17) Rev 6/75

Travel

SOUTHWEST RESEARCH INSTITUTE
San Antonio, Texas 78284

Date: 12-06-1

Project: 17-7234-004

VIDEO	CUT #	PH O^2	FLOW PRESSURE	PH FUEL PRESSURE	FLOW PRESSURE	CUTTING OXYGEN	FLOW PRESSURE	TRAVEL	STAND-OFF	APPEARANCE
					HPN-3		Tip			
766 ✓	B-24	24	52	24	20	80	68	10 ipm	10 mils	Good
787	B-25	24	52	24	20	80	68	15 ipm.		9½ Gouged Lost My Cut
798 ✓	B-26	24	52	24	20	80	68	11½ ipm		Fairly Good
810 ✓	B-27	24	52	24	20	80	68	13¼		Gouged Several Spots
831 ✓	B-28	24	52	24 Adjusted	20	My Gap	68	13¼'		Good
841 ✓	B-29	24	52	24	20	80	68	15"		Lost Cut 2"
855	B-30	24	52	24	20	80	68	14		Good Cut except at the [illegible]
865	B-31	24	52	24	20	80	68	14		Lost Cut 3"
878	B-32	24	52	24	20	80	68	13½		Good
892	B-33	24	52	24	20	80	68	13½		2 Gouged Areas
901	B-34	24	52	24	20	80	68	13½		Good
912 ✓	B-35	24	52	24	20	80	68	8"		Good
927 ✓	B-36	24	52	24	20	80	68	6"		Good Melting Top [illegible]
944 ✓	B-37	24	52	24	20	80	68	4"		Excessive Melting of Top Surface & Some Gaps

Date:______________ Signature:______________

(SwR 17) Rev 6/75

Cutting Oxygen Pressures

SOUTHWEST RESEARCH INSTITUTE
San Antonio, Texas 78284

Date: 12-06-82
Project: 17-7234-004

	CUT #	PH O^2	FLOW PRESSURE	PH FUEL PRESSURE	FLOW PRESSURE	CUTTING OXYGEN	FLOW PRESSURE	TRAVEL	STAND-OFF	APPEARANCE
VIDGO				HPN-3 Tip						
971 ✓	B-38	24	52	24	20	70	63	12"		Good
987 ✓	B-39	24	52	24	20	60	54	12"		Gouged
				HPN-3					12-08-82	
START OF TAPE #8 0 ✓	B-40	24	52	24	20	60	54	10"		No Good Gouged
43 ✓	B-41	24	52	24	20	65	57	12"		Gouged
70 ✓	B-42	24	52	24	20	65	57	10"		Good
96	B-43	24	52	24	20	65	57	8"		Good
129	B-44	24	52	24	20	65	57	6"		Slight Melting on Surface - Good
172 ✗	B-45	93	80 36	47	36	48	44	12		No Good

Date:

Signature:

(SwR 17) Rev 6/75

SOUTHWEST RESEARCH INSTITUTE
San Antonio, Texas 7828[illegible]

Date: [illegible]

Project: 17-7234-004

VDEO	CUT #	PH O^2	FLOW PRESSURE	PH FUEL PRESSURE	FLOW PRESSURE	CUTTING OXYGEN	FLOW PRESSURE	TRAVEL	STAND-OFF	APPEARANCE
				HPN-3 Tip						
188 ✓	B-46	24	52	24	20	50	45	12 i.p.m	15 mils	Gouging
209	B-47	24	52	24	20	80	69	12 i.p.m		Gouging
230	B-48	24	52	24	20	50	48	2 i.p.m		Bad Gouging
	B-49	24	52	24	20	75	65	8 i.p.m		Bad Gouging
278 ✓	B-50	24	52	24	20	50	45	10 i.p.m		Bad Gouging
298 ✓	B-51	24	52	24	20	75	63	10 i.p.m		Bad Gouging
17 ★ ✓	B-52	24	52	10	9	70	61	10 i.p.m		Cannot start cut
✓	B-53	24	52	15	12	70	61	10 i.p.m		Gouging [illegible]
350	B-54	24	52	25	18	70	61	10 i.p.m		Good
377	B-55	24	52	30	21.5	70	61	10 i.p.m		Good
397 ✓	B-56	24	52	40	29	70	61	10 i.p.m		Good
417 ✓	B-57	30	35	24	20	70	61	10 i.p.m		Lost Cut After 3"
433 ✓	B-58	40	46	24	20	70	61	10 i.p.m		Good
459 ✓	B-59	60	66	24	20	70	61	10 i.p.m		Good
483 ✓	B-60	70	77	24	20	70	61	10 i.p.m		Good 1st [illegible]" & last 3" Gouging
505	B-61	70	77	24	20	70	61	10 i.p.m		Good 1st 3" and last 5" Were about 4 gouges

Date:

(SwR 17) Rev 6/75

Signature:

SOUTHWEST RESEARCH INSTITUTE
San Antonio, Texas 78284

Date: 01-31-83

Project: 17-7234-004

CUT #	PH O^2	FLOW PRESSURE	PH FUEL PRESSURE	FLOW PRESSURE	CUTTING OXYGEN	FLOW PRESSURE	TRAVEL	STAND-OFF	APPEARANCE
				3/4" Thick Plate (Different Supplier)					
			Travel						
1	22	45	12	45	40	28	15	1/4	
2	22	45	12	45	40	28	15	Raised to 5/16"	
3	22	21	12	16	40	28	15	5/16	
4	22	21	12	16	40	28	~~20~~	5/16	Specimen [illegible] Fell [illegible]
5	22	21	12	16	40	28	10		
			Cutting Oxygen						
6	22	21	12	16	30	23	15		
7	22	21	12	16	20	17	15		
				02-01-83 + 02-02-83					
			Bevel Cuts 3/4 Armor Plate (Different						
									Supplier)
8(1B)	22	38	12	16	40	29	15	20 mil	[illegible]
9(2B)							10		Gouged
10(3B)							10		Gouged
11(4B)							12		Gouged
12(5B)	22	28	12	21	40		12		Gouged
13(6B)	22	41	18	26	45	35	12		Gouged
14(7B)	40	46	24	20	70	61	12		Gouged
15(8B)	40	46	24	20	70	61	16		Good
16(9B)	40	46	24	20	70	61	16		Gouged

Date: ________ Signature: ________

(SwR 17) Rev 6/75

[illegible]

San Antonio, Texas 78284

Project: 17-7234-004

Bevel Cuts (1in)

CUT #	PH O^2	FLOW PRESSURE	PH FUEL PRESSURE	FLOW PRESSURE	CUTTING OXYGEN	FLOW PRESSURE	TRAVEL	STAND-OFF	APPEARANCE
17(10B)	40	46	24	20	70	61	12	20 mil	Good
18(11B)	40	46	24	20	70	61	10	20 mil	Good
19(12B)	40	46	24	20	70	61	8	20 mil	Good [illegible]
20(13B)	40	46	24	20	70	61	15	20 mil	Good
21(14B)	40	46	24	26	70	61	15	60 mil	Several Gouges
					02-03-83				Did not [illegible]
22(15B)	40	46	15	12	70	61	14	20 mil	Lost Cut [illegible]
23(16B)	40	46	15	12	70	61	10	20 mil	Gouged
24(17B)	40	46	25	18	70	61	12	20 mil	Good - but has 3 gouges
25(18B)	40	46	30	22	70	61	12	20 mil	Good
26(19B)	40	46	40	29	70	61	12	20 mil	Good
27(20B)	30	35	24	20	70	61	12	20 mil	Good [illegible]
28(21B)	60	66	24	20	70	61	12	20 mil	Gouging [illegible]
29(22B)	60	66	24	20	70	61	10	20 mil	Several Gouges
30(23B)	70	77	24	20	70	61	10	20 mil	No Good Gouges
			Straight Cuts 1"						
31 8	22	45	12	45	40	28	15	5/16 +	Good
32 9	22	21	12	16	40	28	15	5/16 +	Good
33 10	22	21	12	16	40	28	20	5/16 +	[illegible] did not fall fr
34 11	22	21	12	16	40	28	10	5/16 +	Good
35 12	22	21	12	16	30	23	15	5/16 +	Good
36 13	22	21	12	16	20	17	15	5/16 +	Did not cut the last of the plate

Date:

Signature:

(SwR 17) Rev 6/75

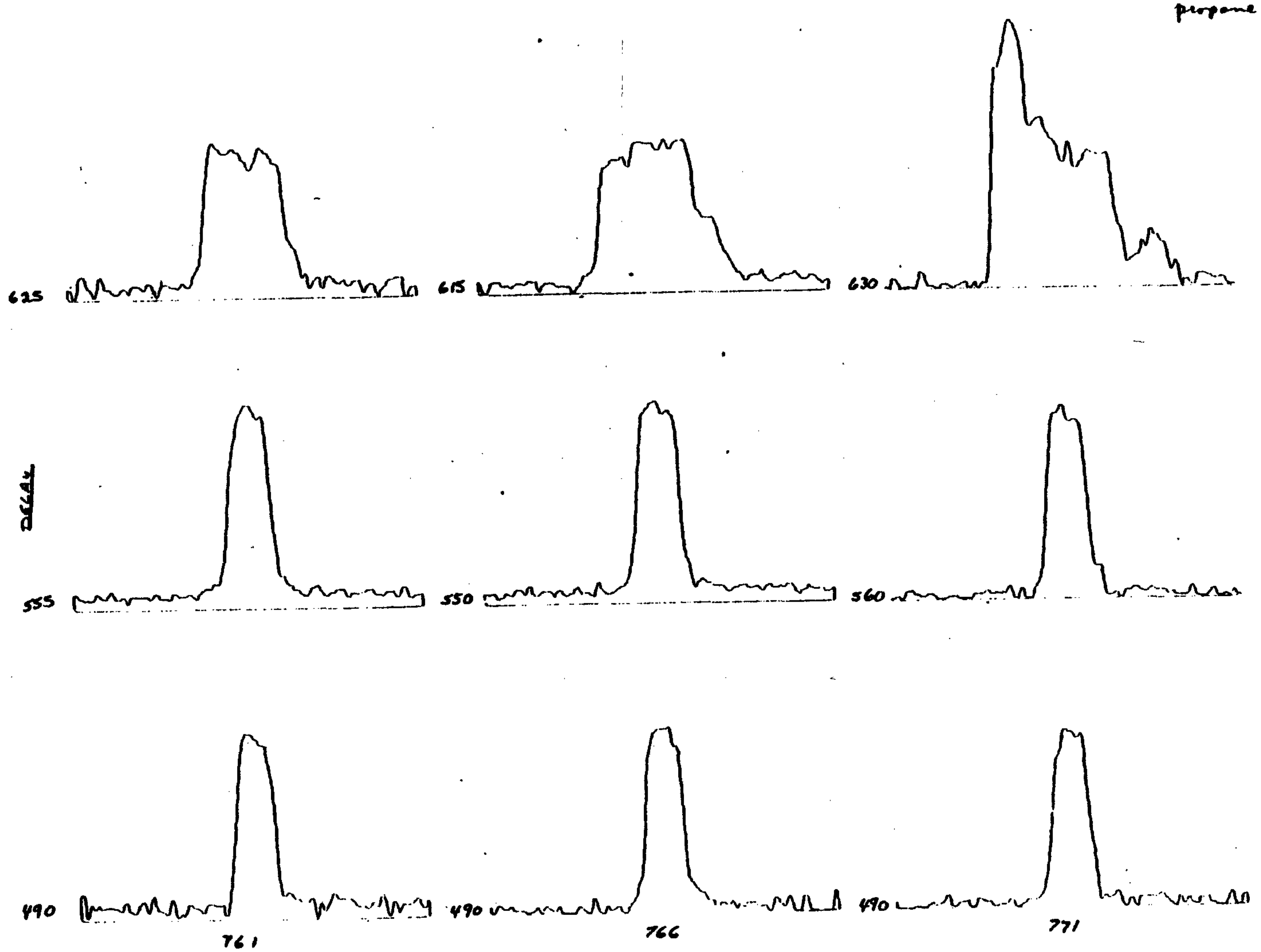
Triple torch cuts 1/18/83

Cut #1	— fiber optic — no good	
Cut #2	HPN#5 leading Speed 8 ipm	good cut
Cut #3	" 10 ipm	Small Gouges near last 3"
Cut #4	speed 8 ipm cutting O_2 90 tipheight ~~.020~~ .020	excellent cut
Cut #5	Same as above tipheight ≅ .100 ; increased speed as we went along to 11 ipm	good cut last end (4") got welded to the plate
Cut #6	Same as #5 speed 4 ipm	not a drop-free cut. Overall good quality only one or two gouges
Cut #7	8 ipm tipheight leading torch rubbing, others different heights, rubs only half way through the plate	not a drop free cut good cut One gouge near the end.
Cut #8	Changed tip to GP#3 on lead torch 8 ipm — slowed down as went along	Top - good Straight - OK Bottom - gouged Bottom - begin good 1/8 ipm
Cut #9	Same as above 8 ipm	not a dropfree cut Top - good St. - OK bottom start 3" good last 2" rest gouges.
Cut #10	#5 HPN tip - increased cutting O_2 pressure	" top good st good bottom [illegible]

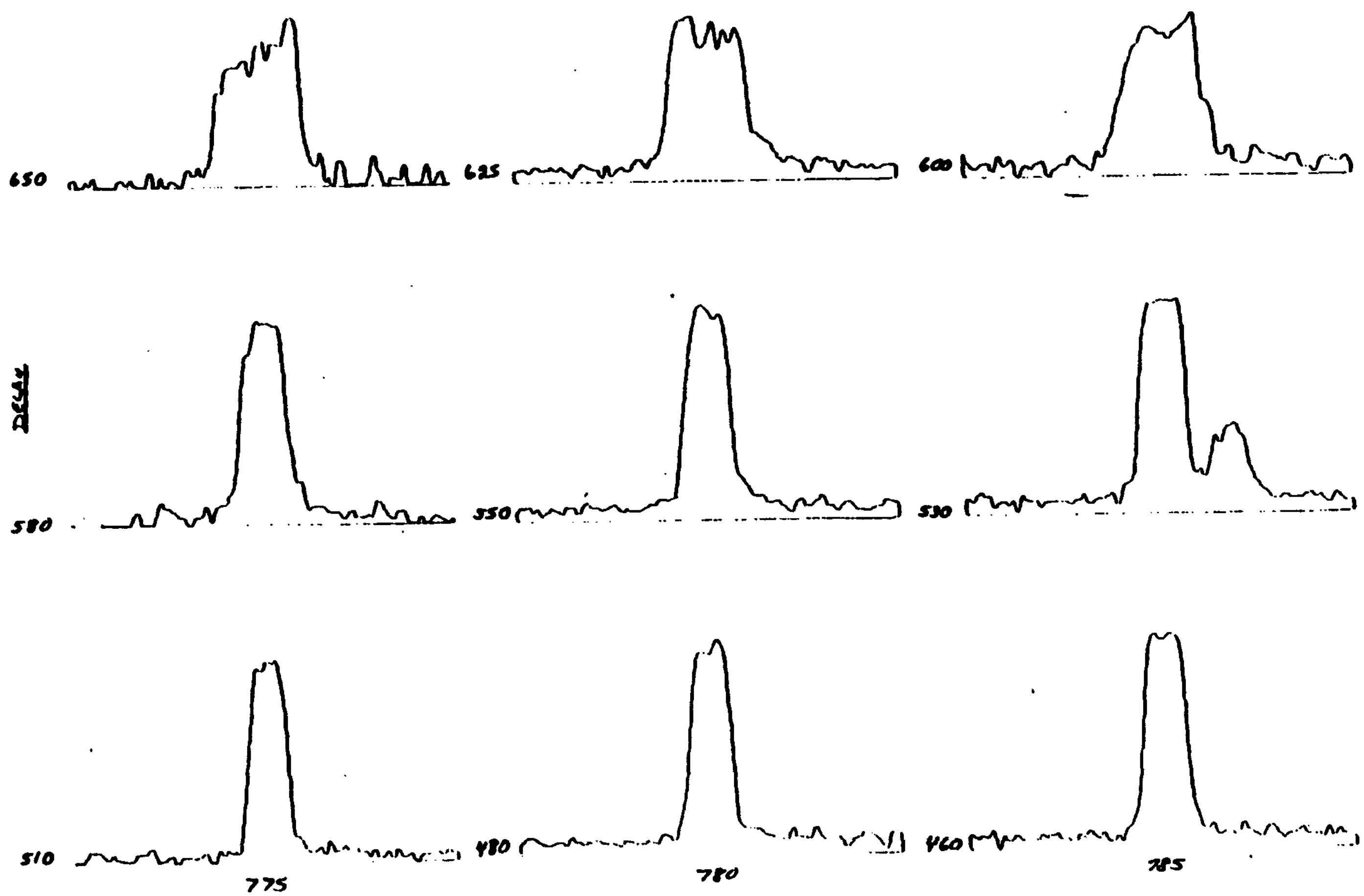
APPENDIX D

TYPICAL TEMPERATURE PROFILES FOR SINGLE TORCH PERPENDICULAR AND BEVEL CUTS, AND TRIPLE TORCH CUTS

Pg. 1 of 1
CAT # 73
VIDEO REEL # 6
propane = 9

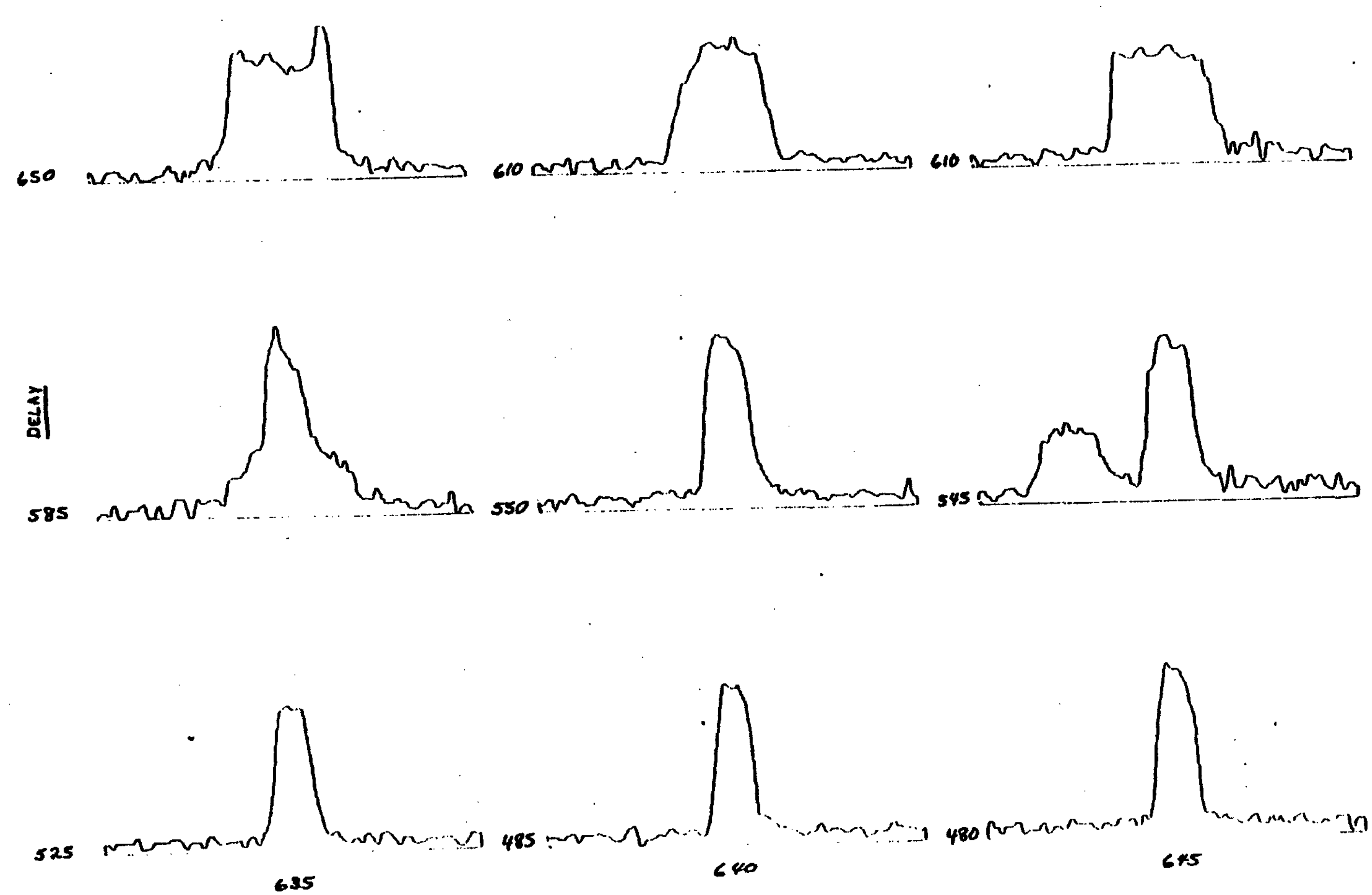


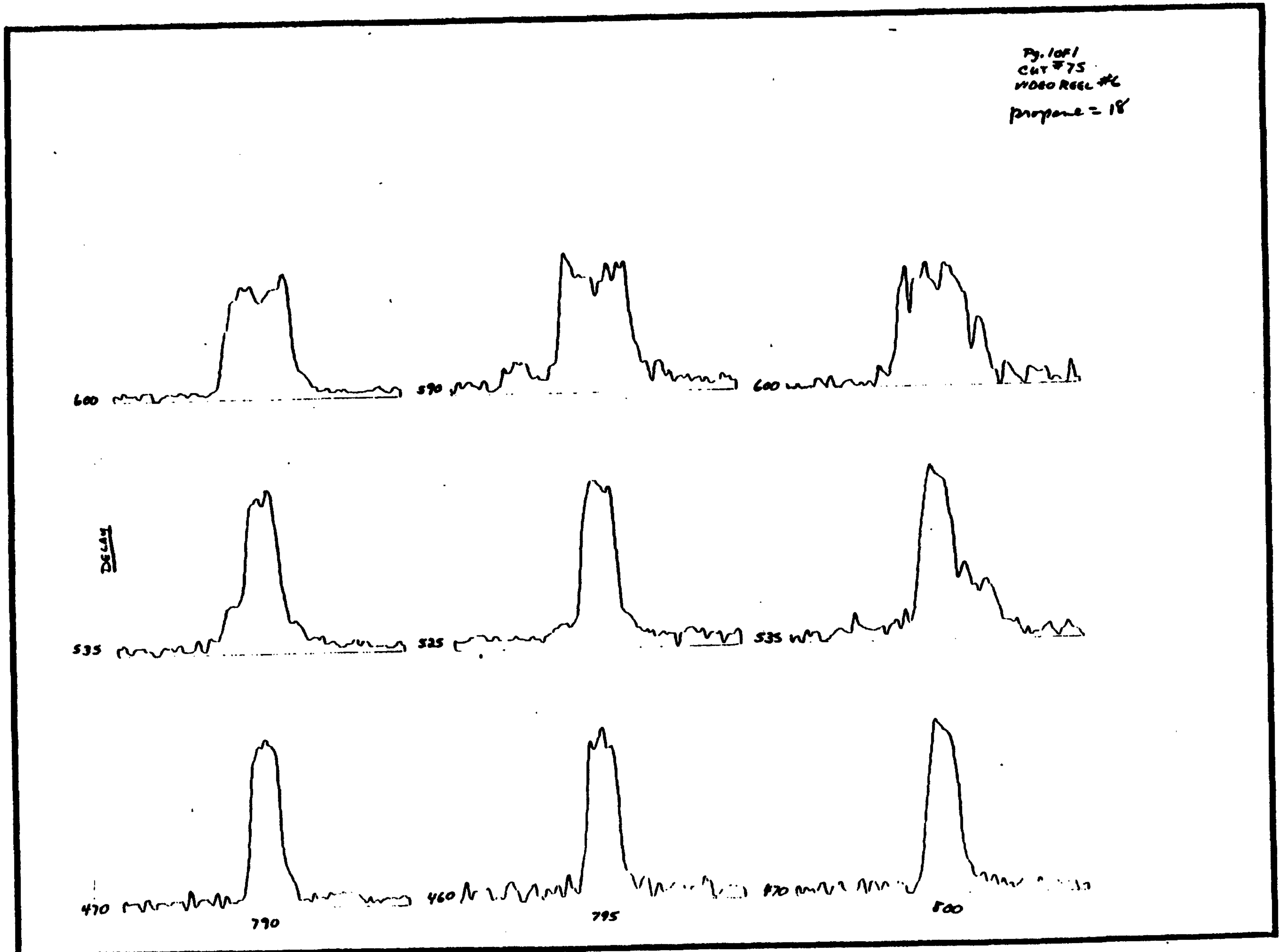
Pg. 1 of 1
CUT # 74
VIDEO REEL #6
purpose = 12



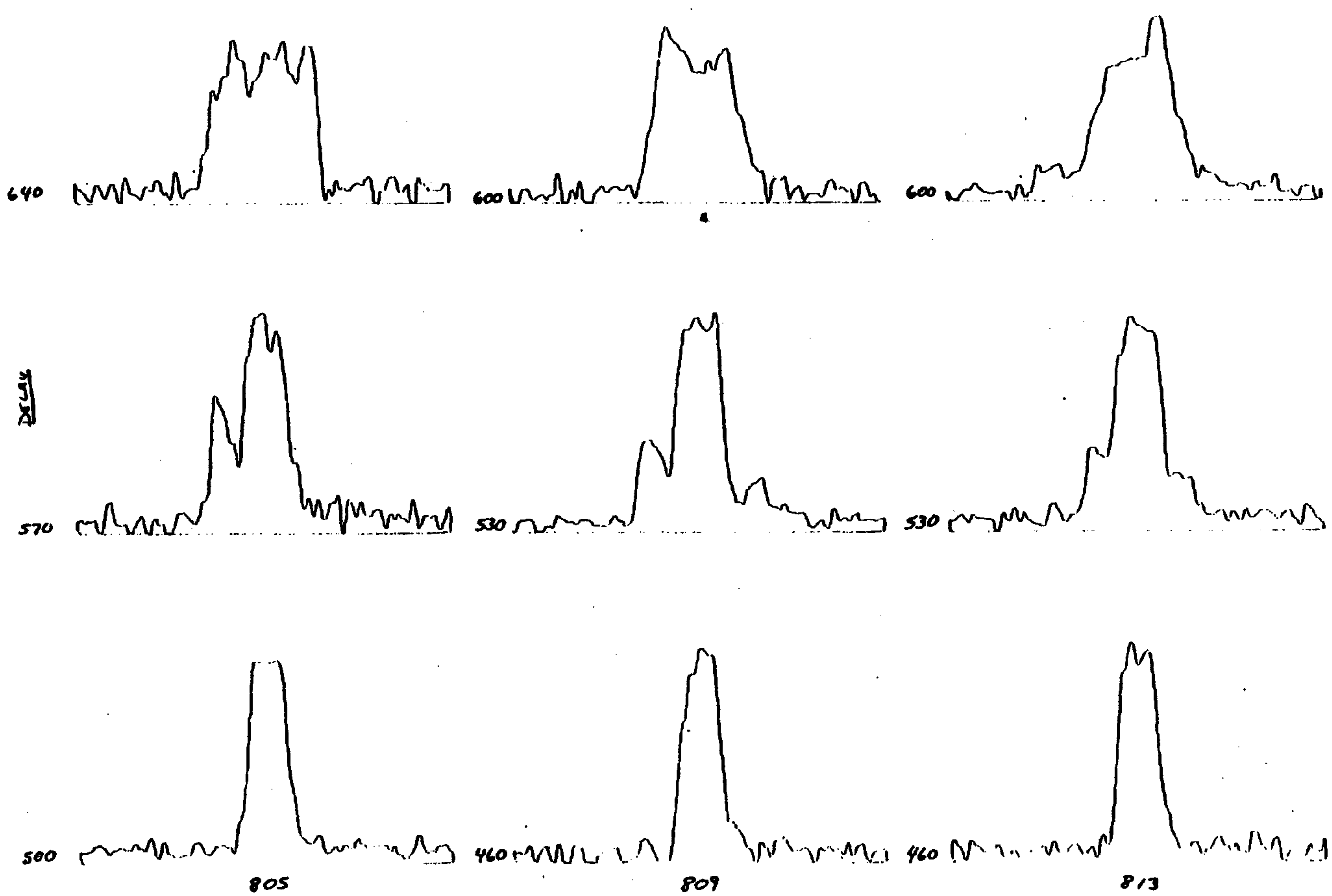
Pg. 1 of 1
CUT # 66
VIDEO REC #6

Propane = 15

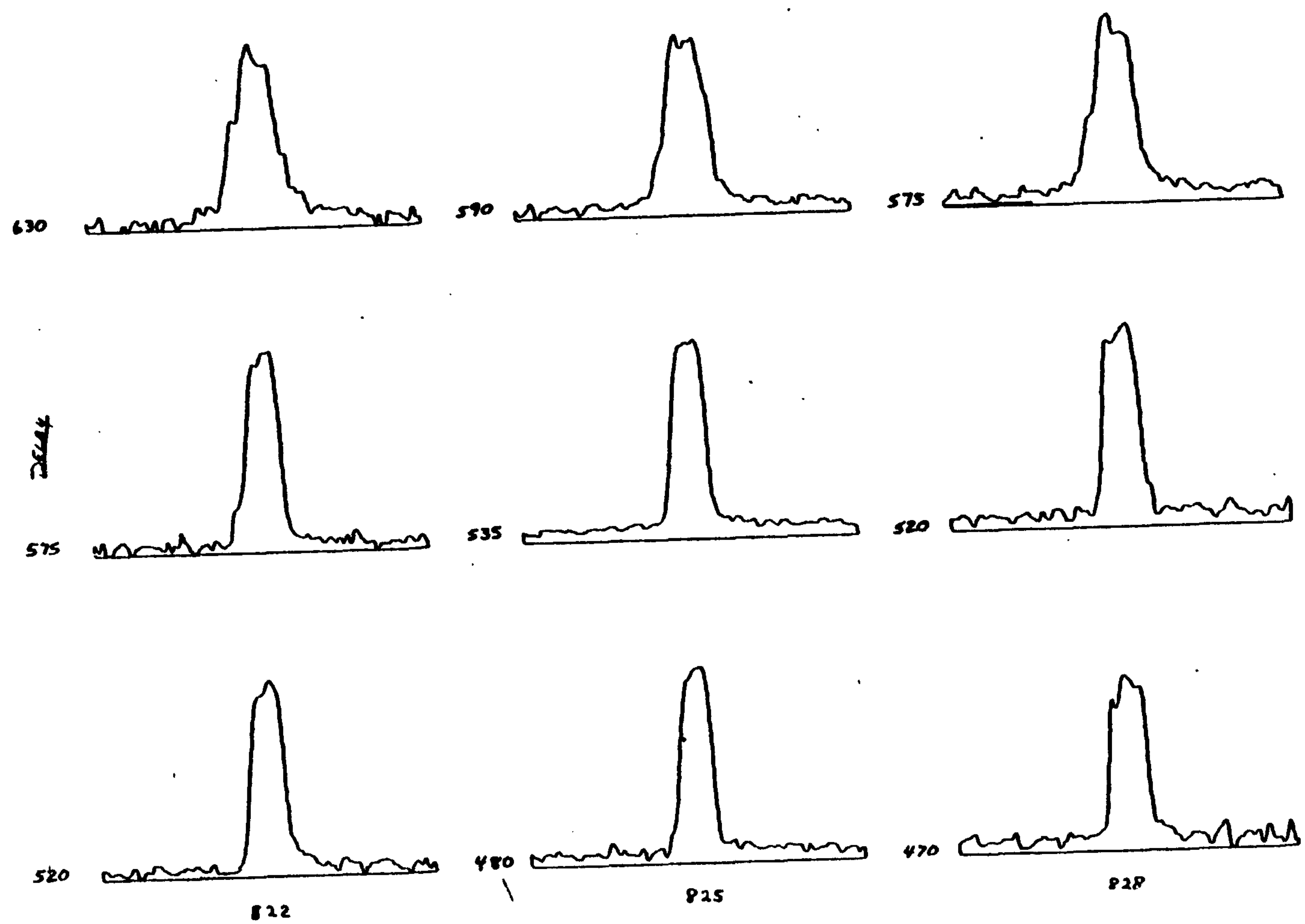



Pg. 1 of 1
CUT #75
VIDEO REEL #6
propane = 18
DELAY
600
590
600
535
525
535
470
790
460
795
870
800

Pg. 1 of 1
Cut # 76
Video Reel #6
propane = 21



Pg 1 of 1
Cut # ▮77
Video Reel #6



Pg. 1 of 1
Cut # 78
Video Reel #6
Propane = 14

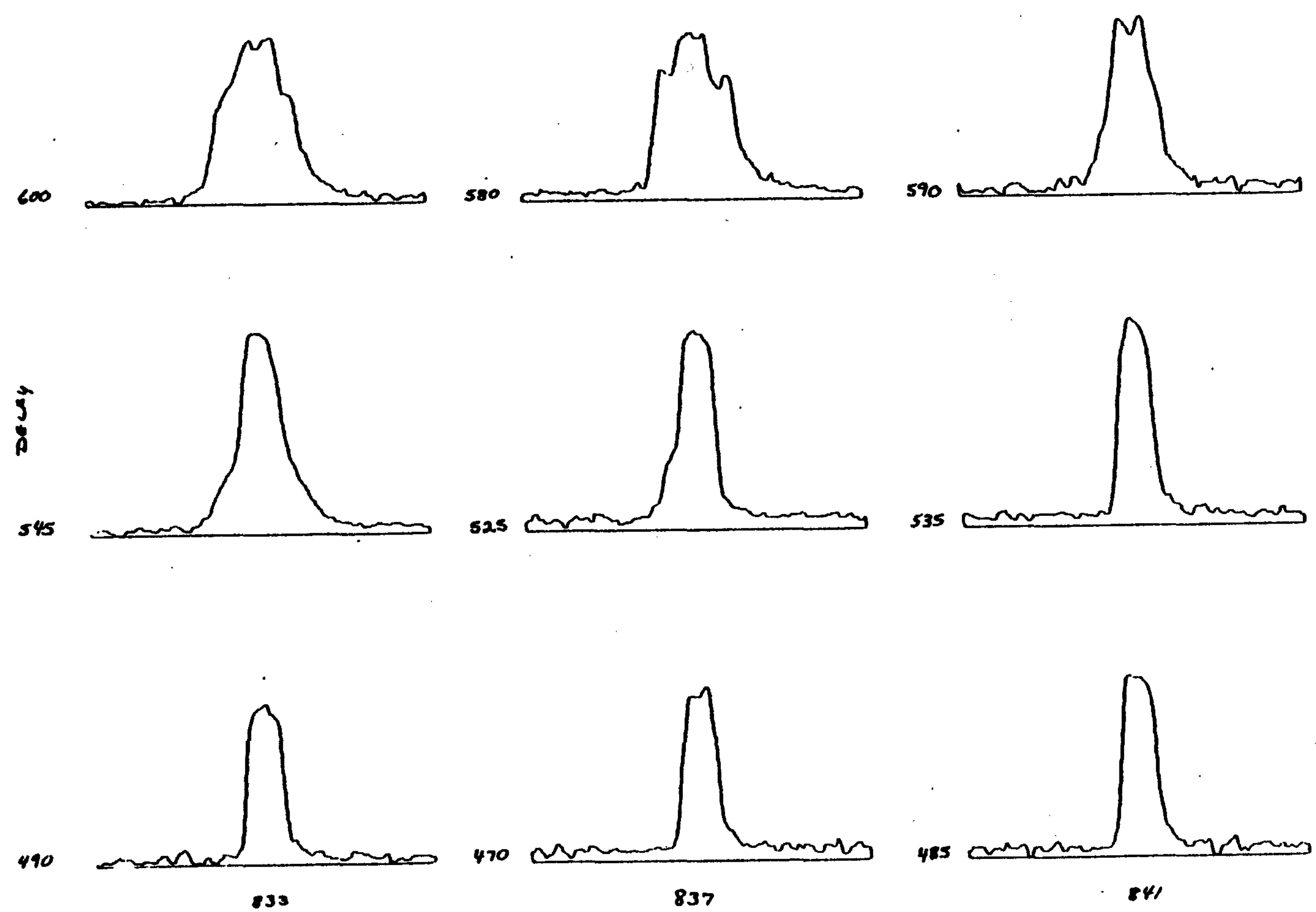
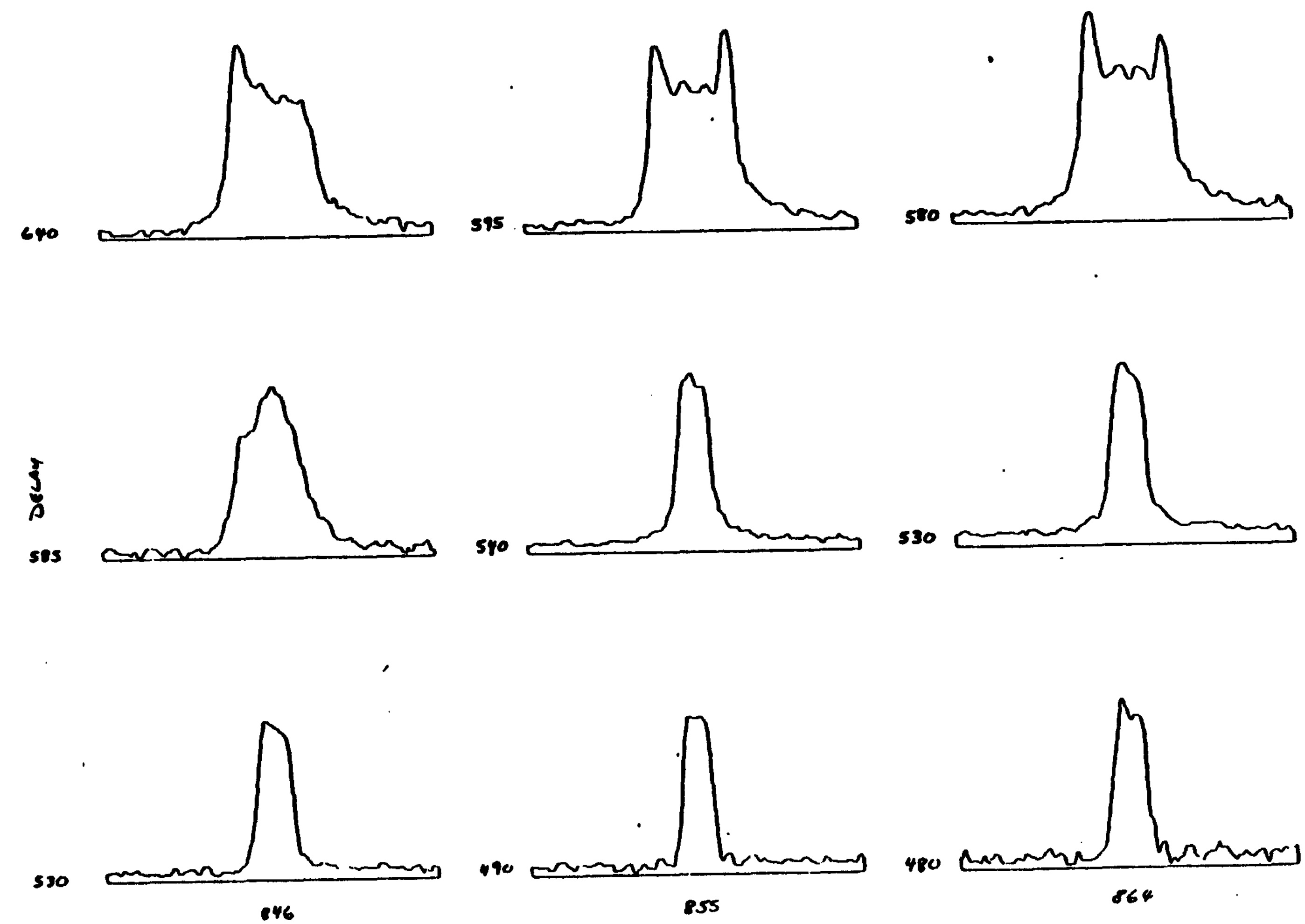
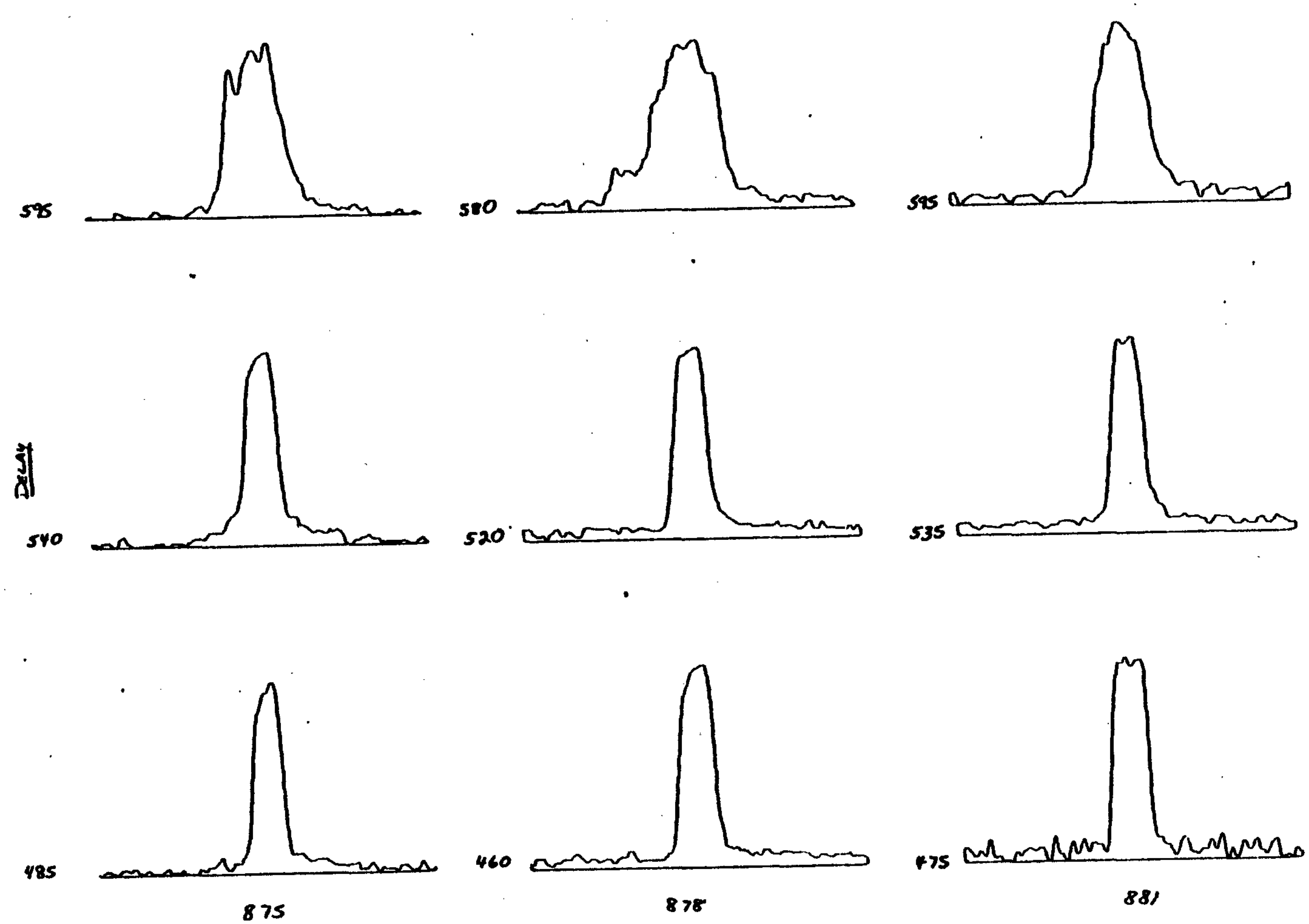


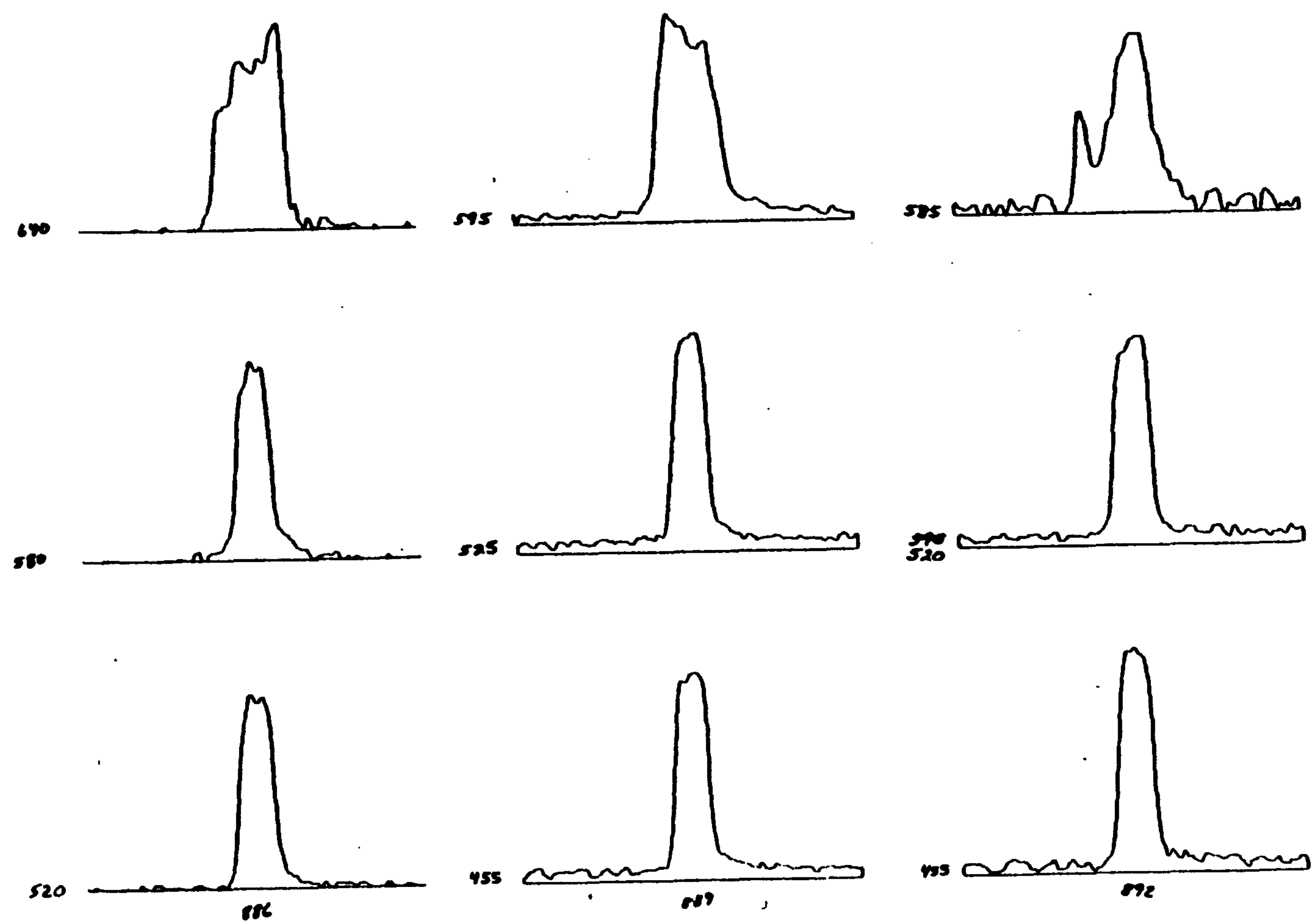
Fig. 1 of 1
CAT # 79
VIDEO REEL # 6



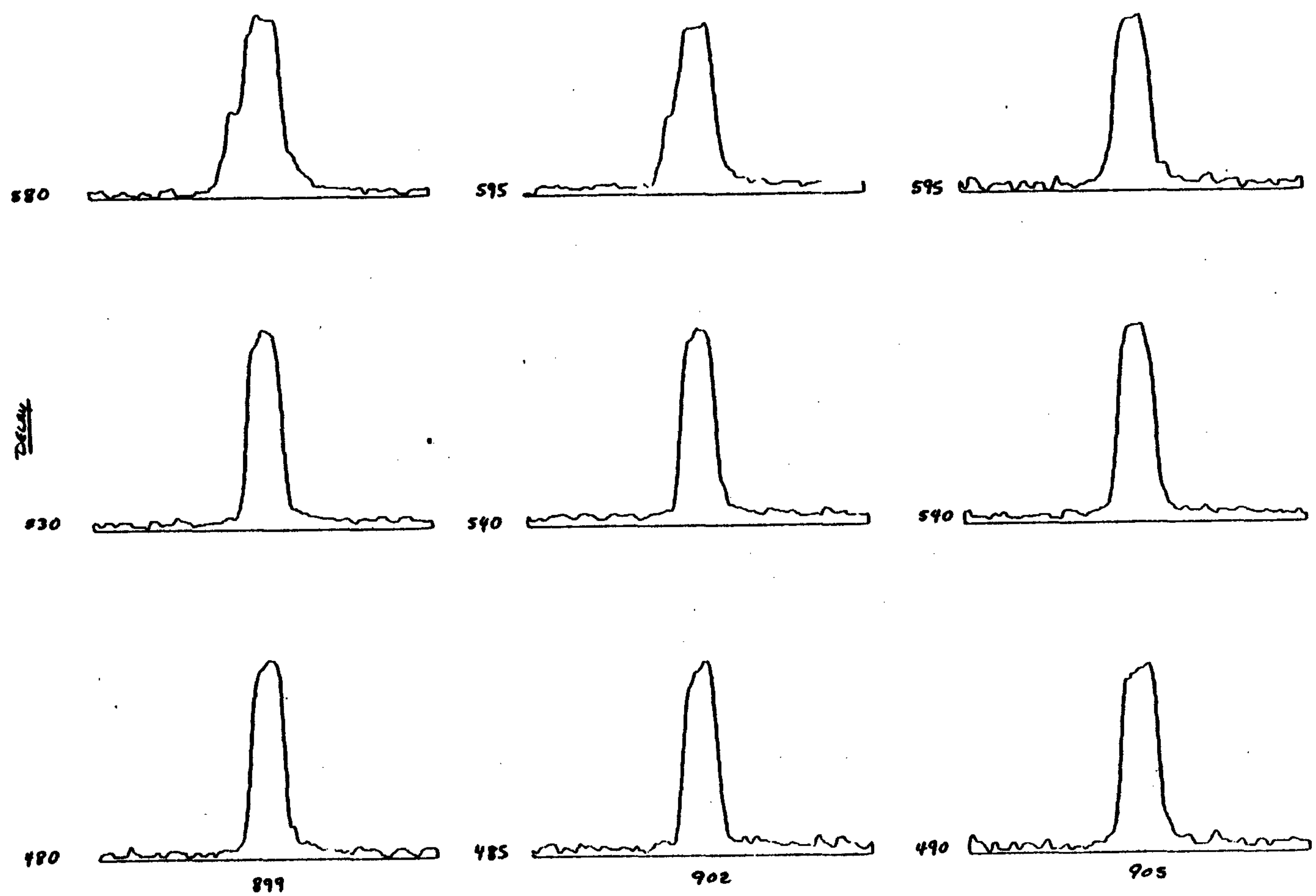
Pg. 1 of 1
CUT #80
VIDEO REEL #6

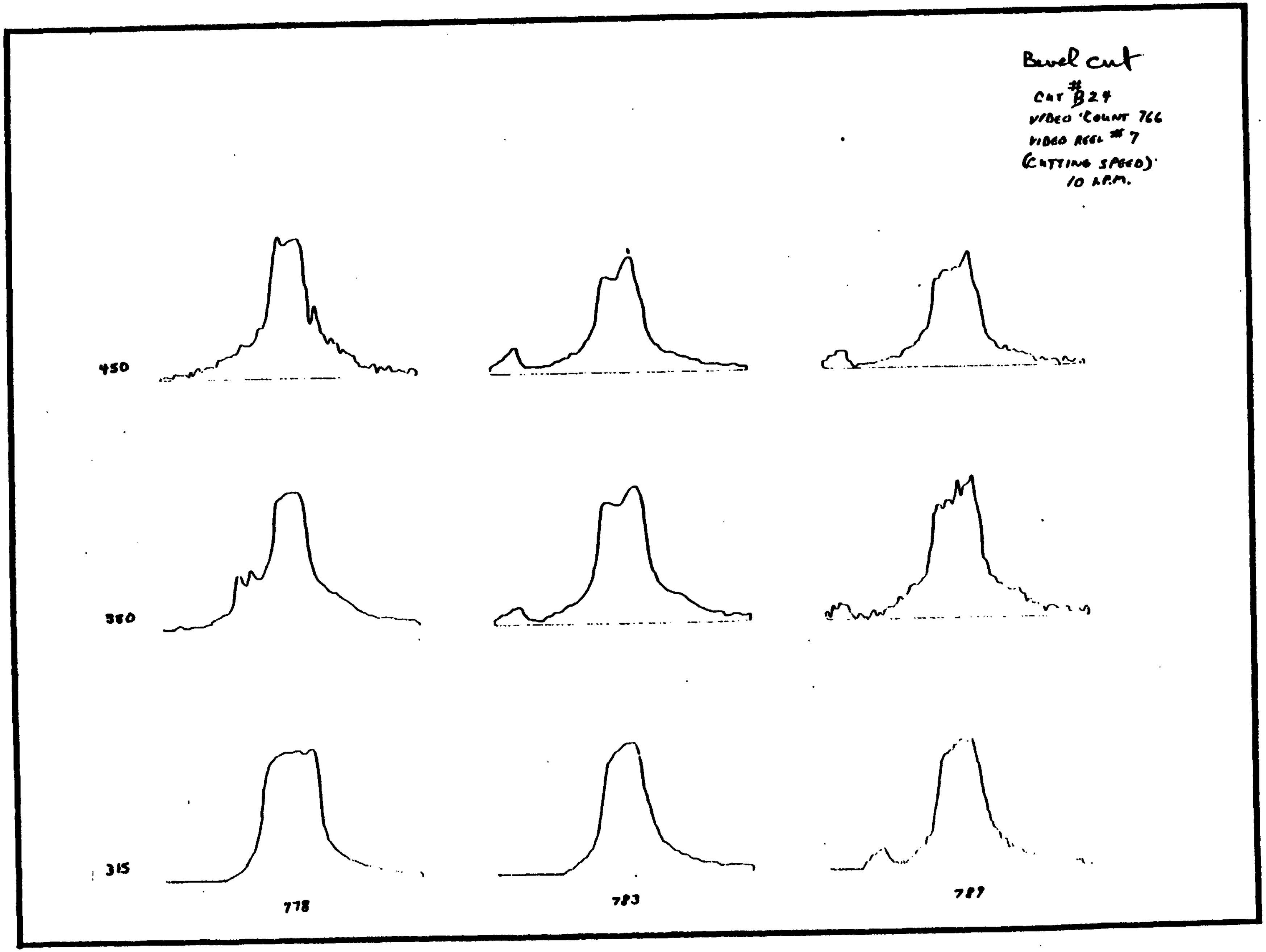


Pg. 1 of 1
Cut #81

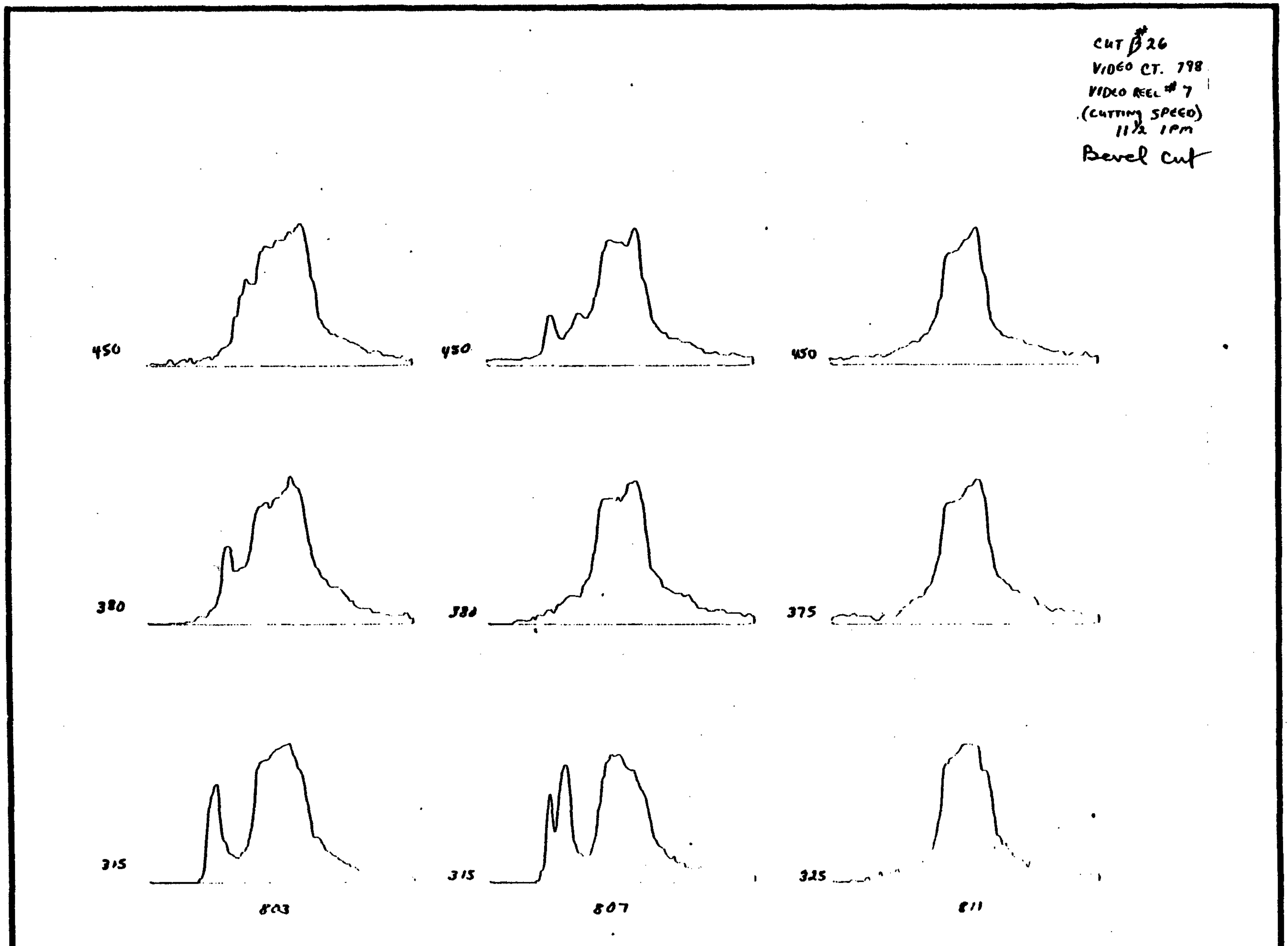


Pg. 1 of 1
CUT # 82
VIDEO REEL #6

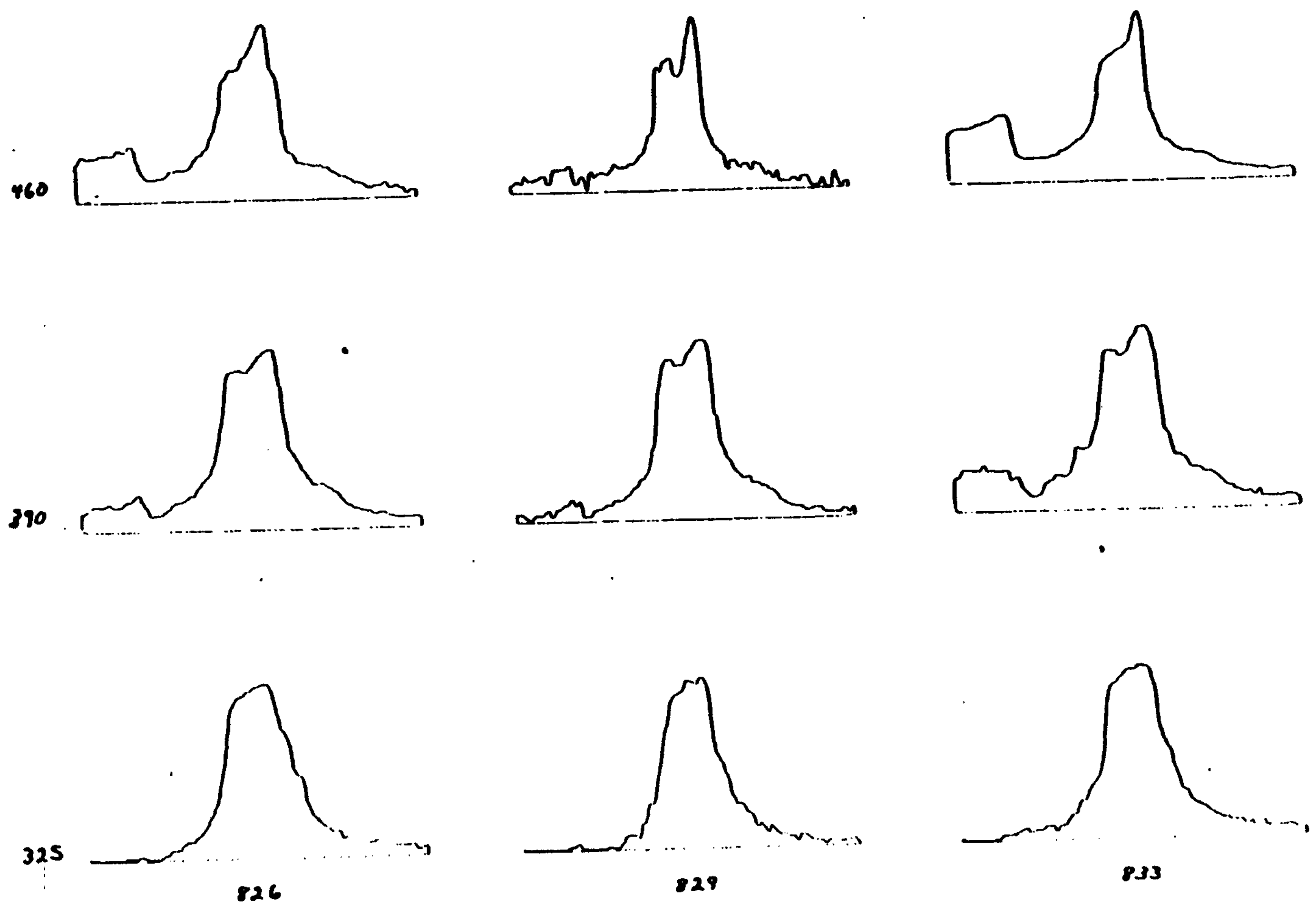




Bevel cut
CUT # B24
VIDEO COUNT 766
VIDEO REEL # 7
(CUTTING SPEED)
10 R.P.M.
450
380
315
778
783
789

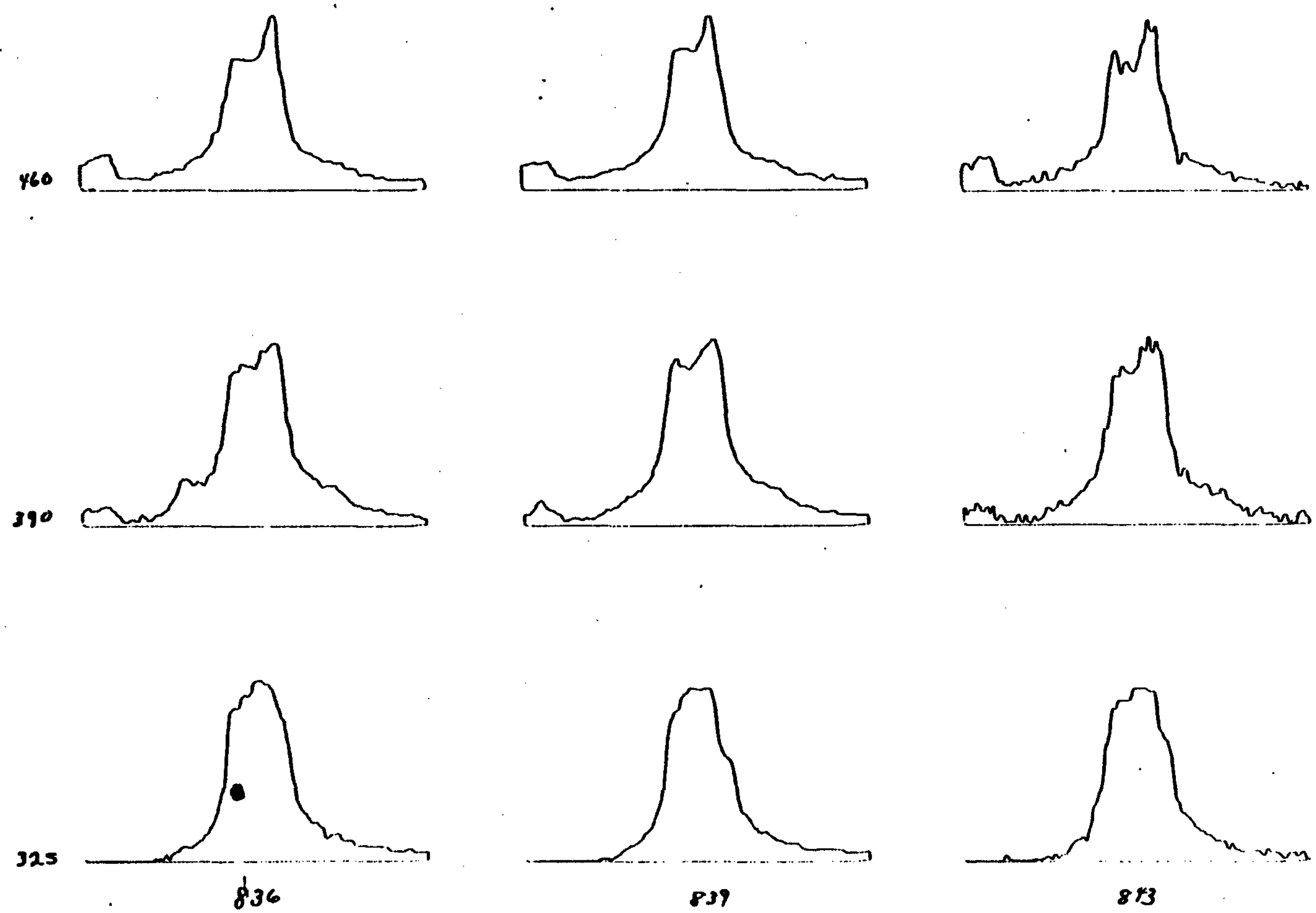

CUT # 26
VIDEO CT. 798
VIDEO REEL # 7
(CUTTING SPEED)
11½ IPM
Bevel Cut
450
450
450
380
380
375
315
315
325
803
807
811

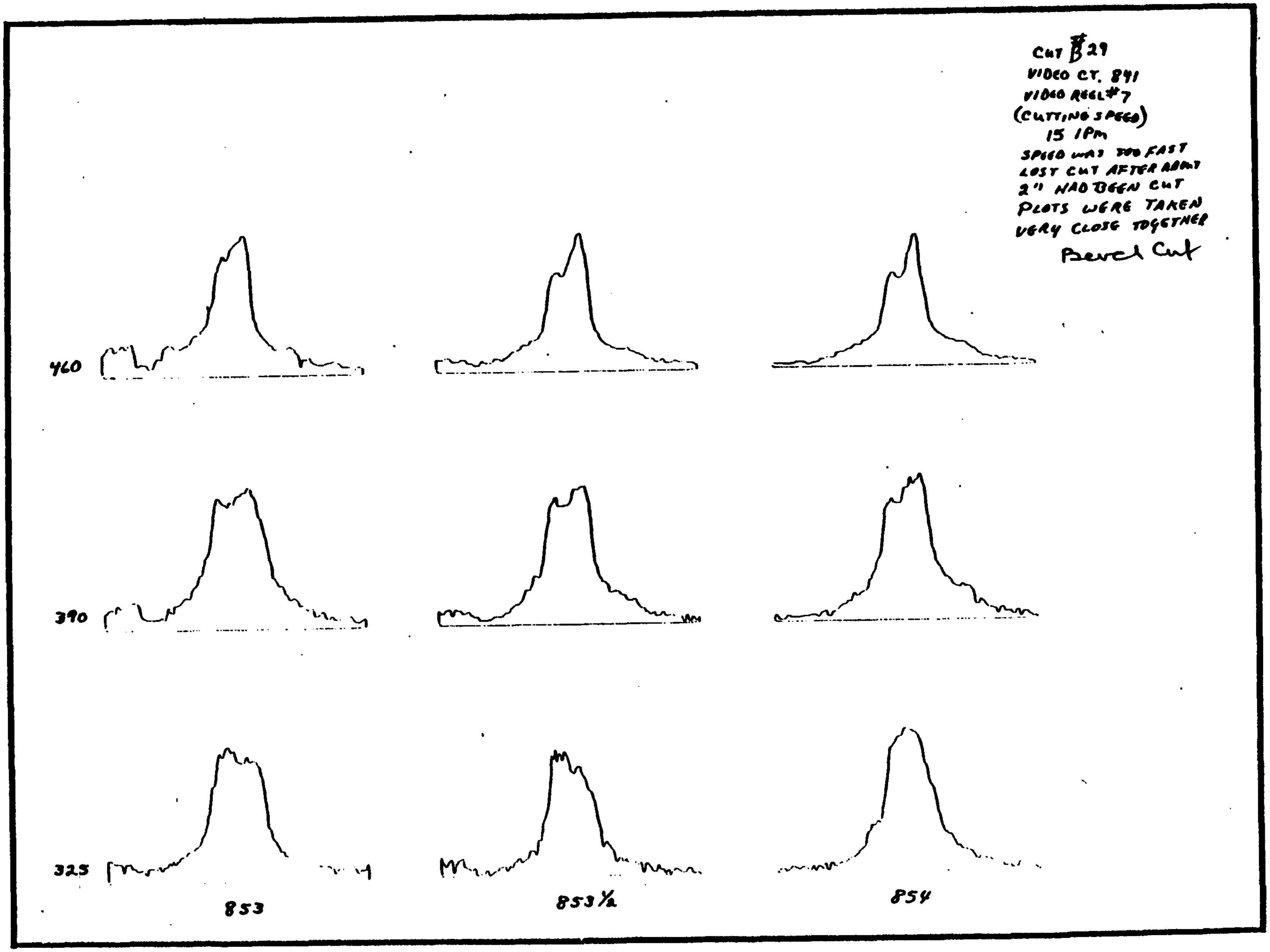
cut # B 27
VIDEO CT 810
VIDEO REEL #7
(CUTTING SPEED)
13 1/4" IPM
Bevel cut



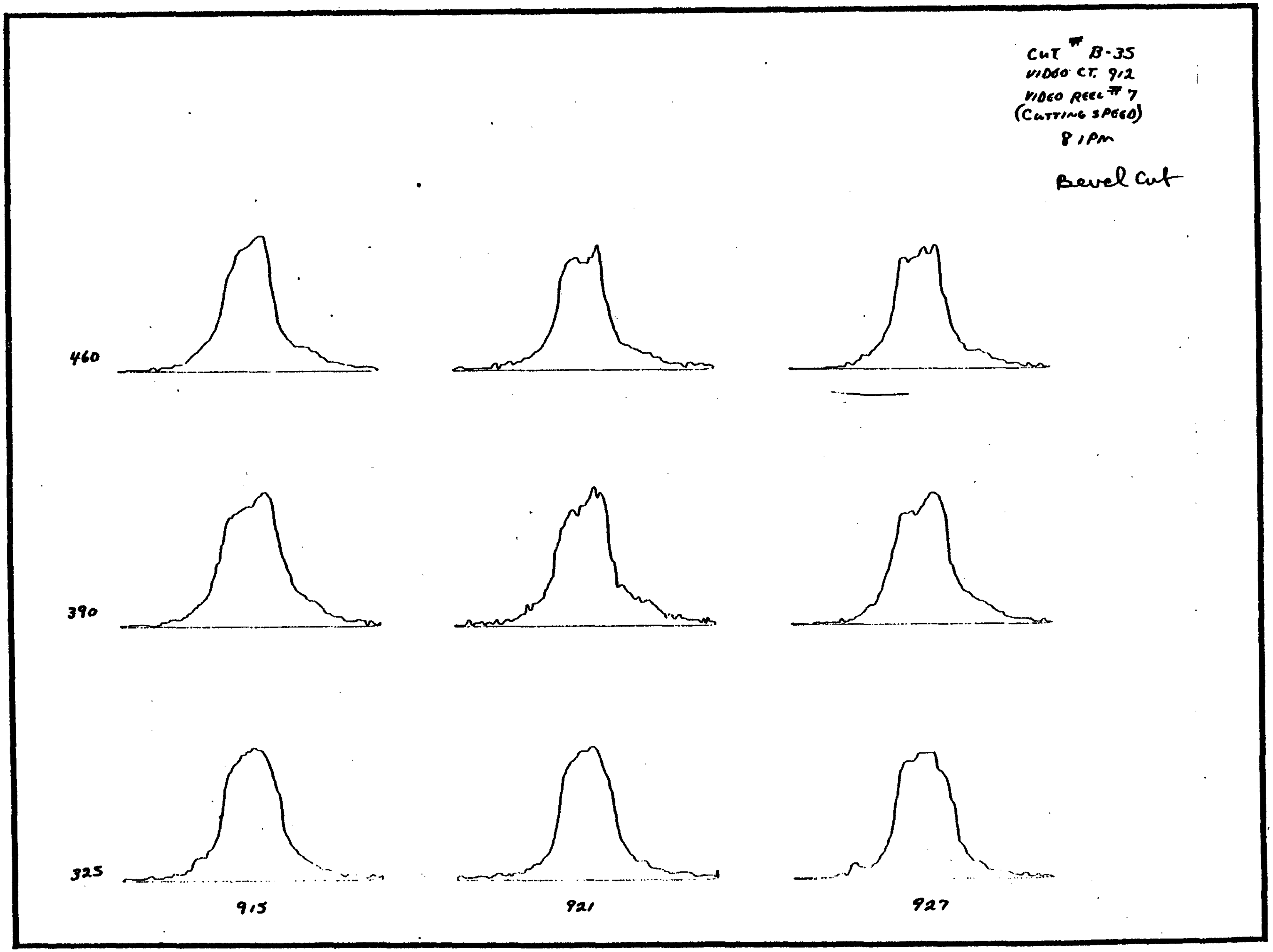
CUT #B28
VIDEO C7, 831
VIDGO REEL #7
(CUTTING SPEED)
13 1/4 r.p.m.

Bevel cut

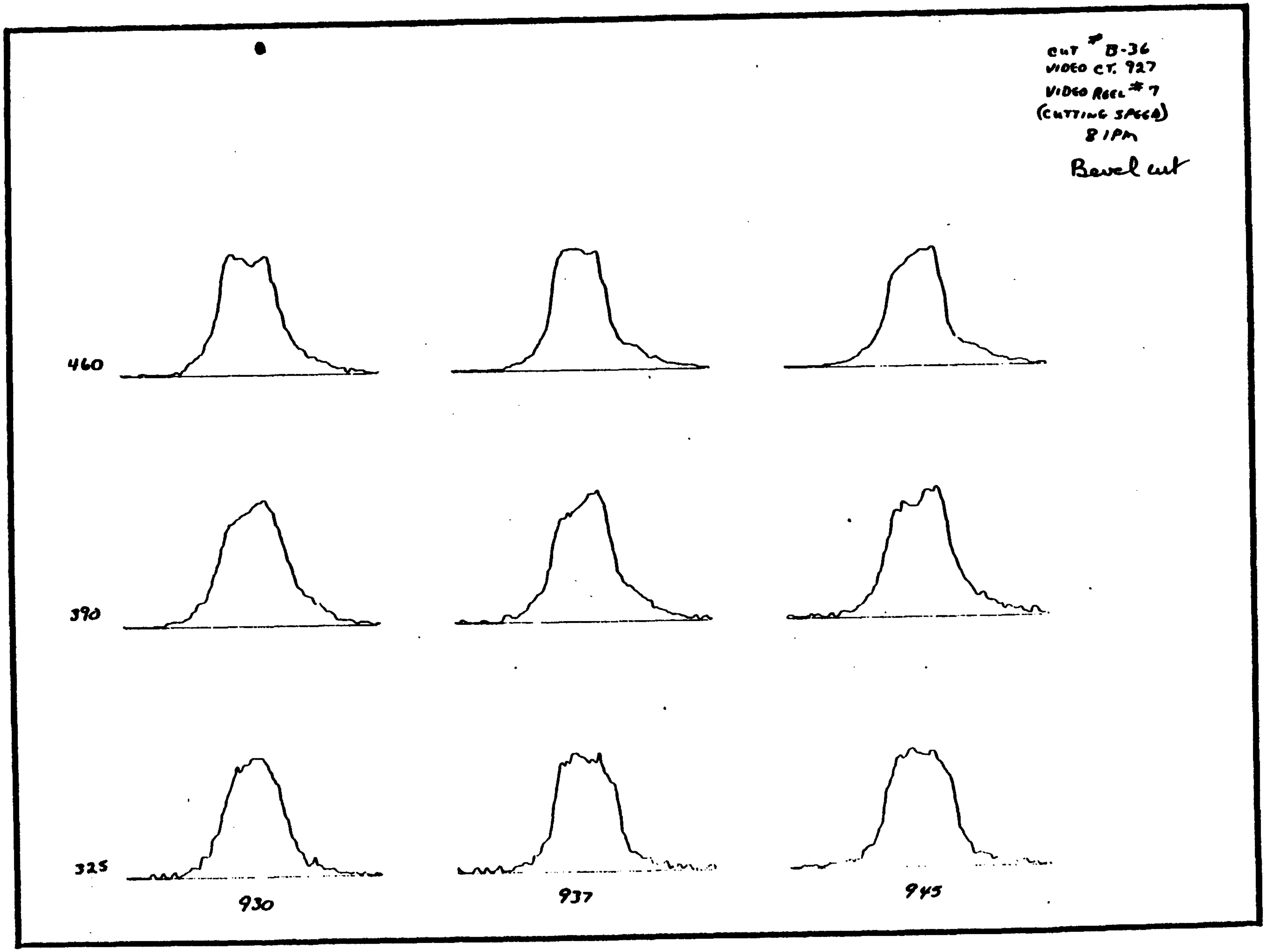




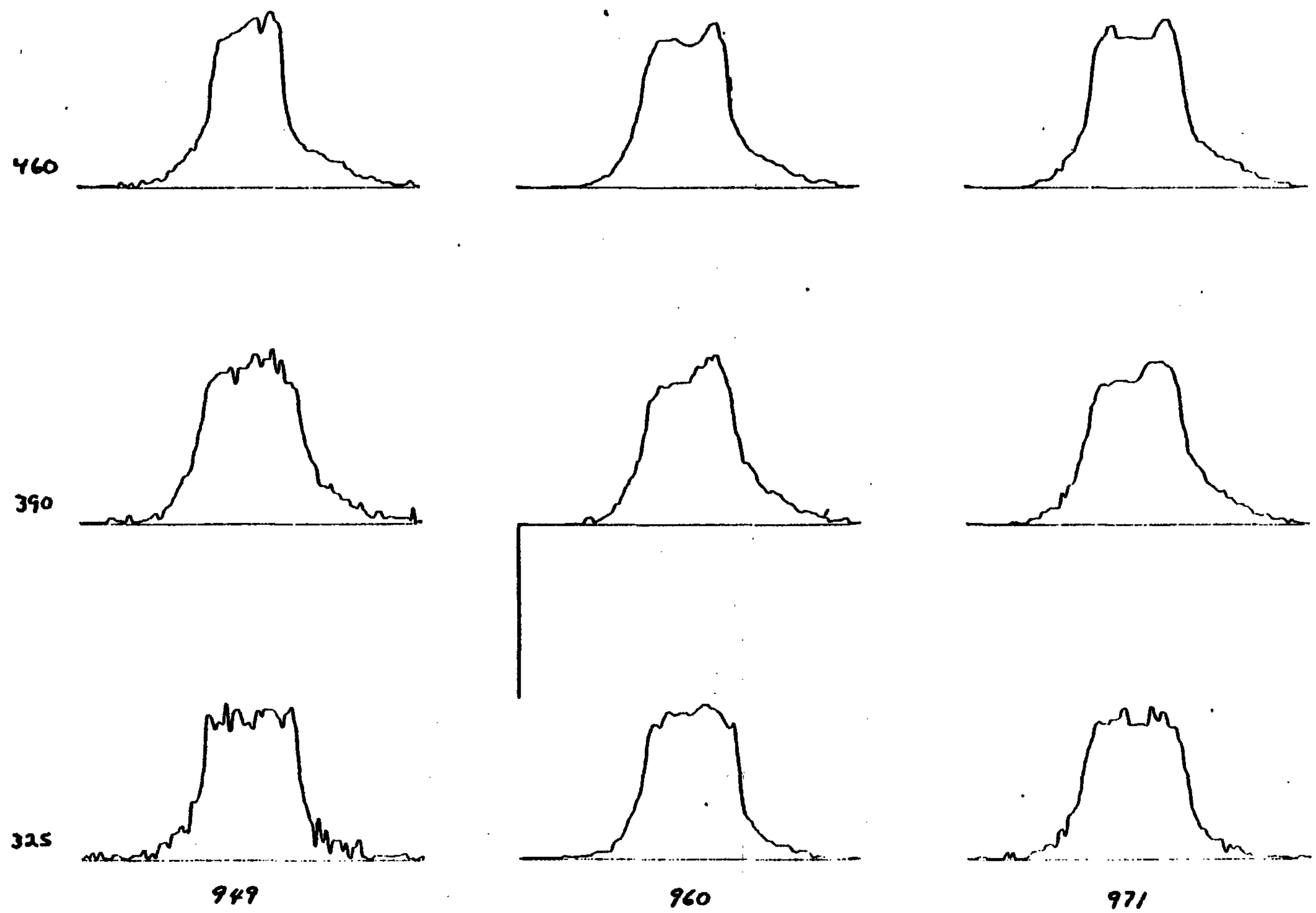
CUT #B29
VIDEO CT. 841
VIDEO REEL #7
(CUTTING SPEED)
15 IPM
SPEED WAS TOO FAST
LOST CUT AFTER ABOUT
2" HAD BEEN CUT
PLOTS WERE TAKEN
VERY CLOSE TOGETHER
Bevel Cut
460
390
325
853
853½
854



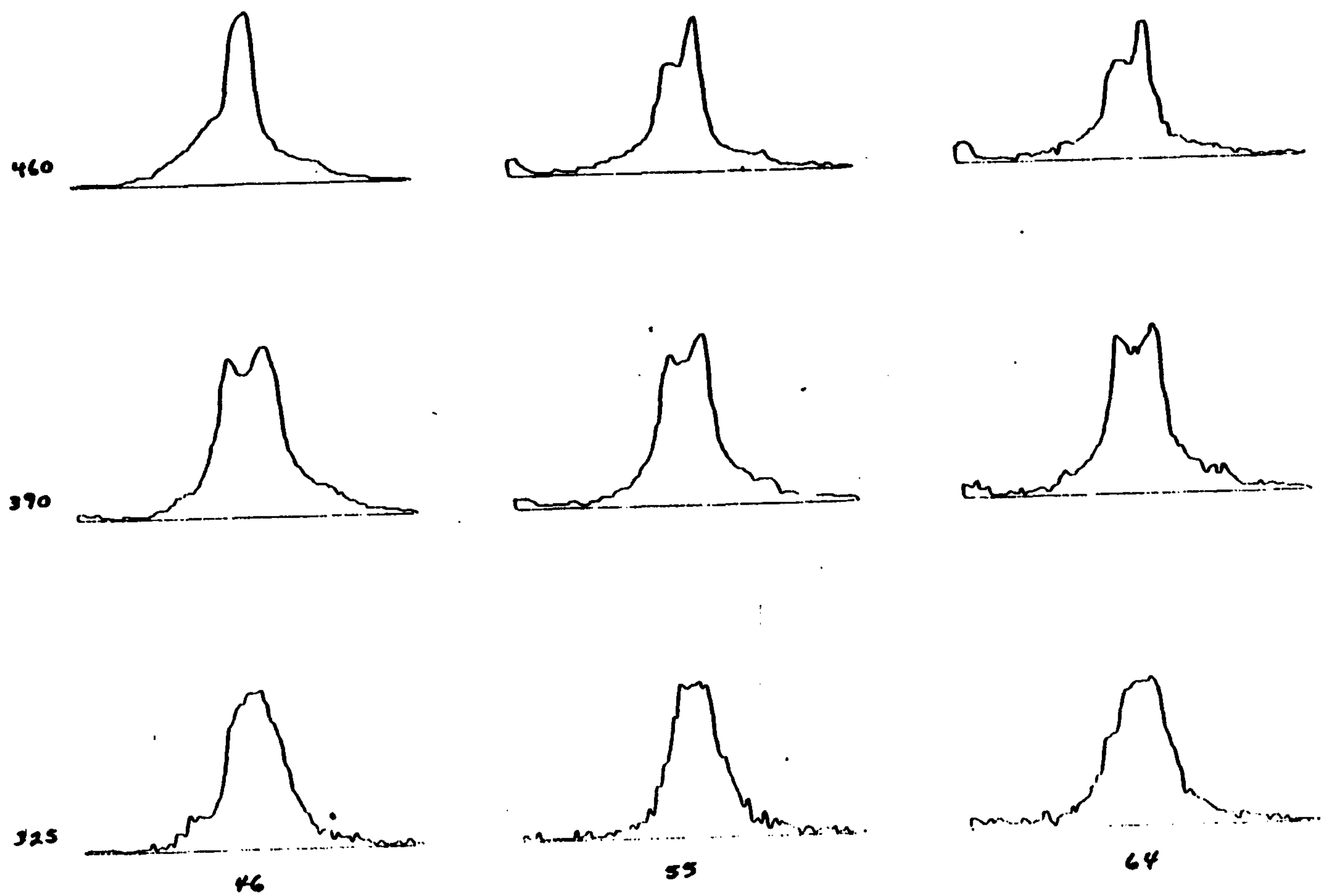
CUT # B-35
VIDEO CT. 912
VIDEO REEL # 7
(CUTTING SPEED)
8 IPM
Bevel Cut
460
390
325
915
921
927

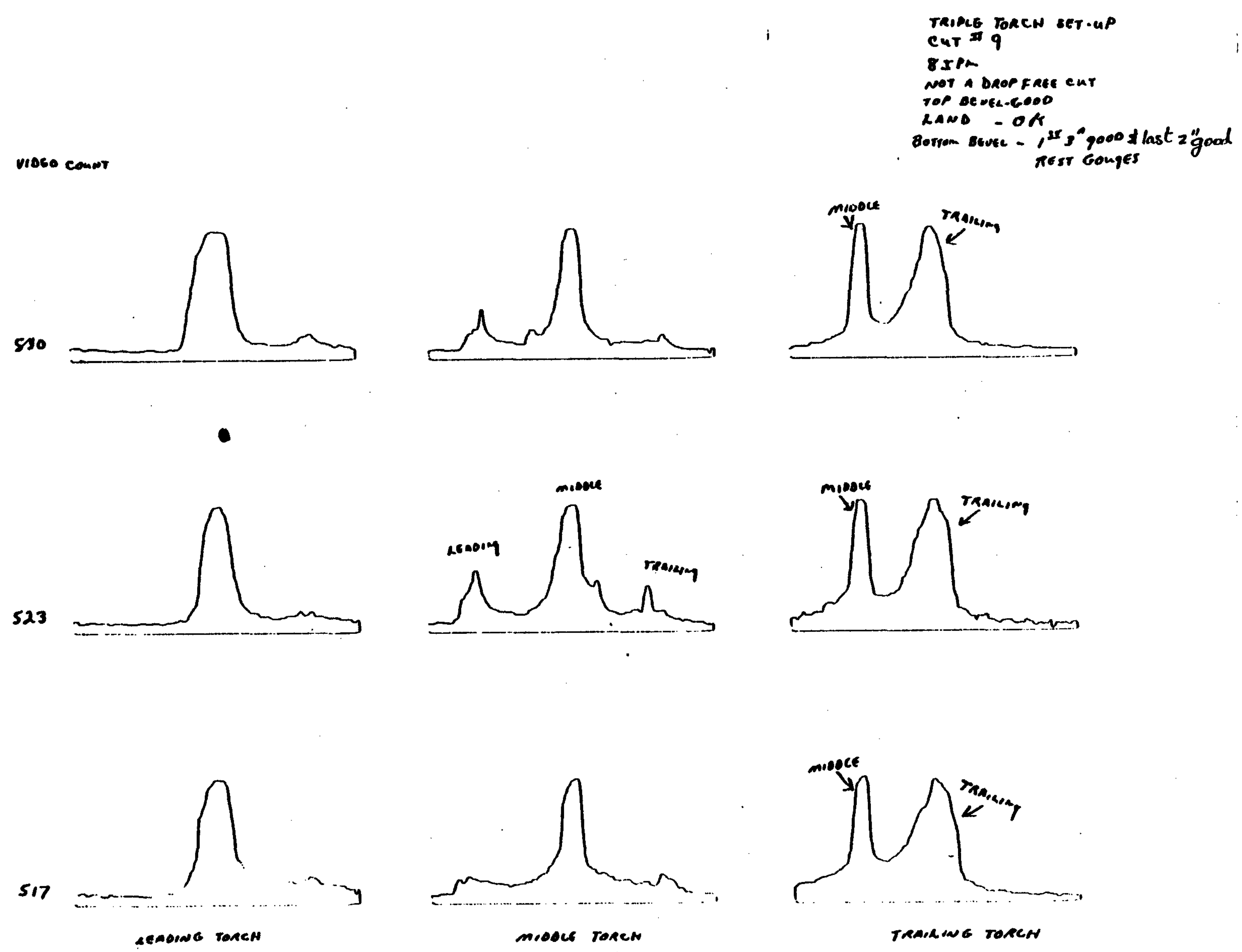

CUT # B-36
VIDEO CT. 927
VIDEO REEL # 7
(CUTTING SPEED)
8 IPM
Bevel cut
460
390
325
930
937
945

CUT # B-37
VIDEO CT. 944
VIDEO REEL # 7
(CUTTING SPEED)
4 IPM
Bevel cut



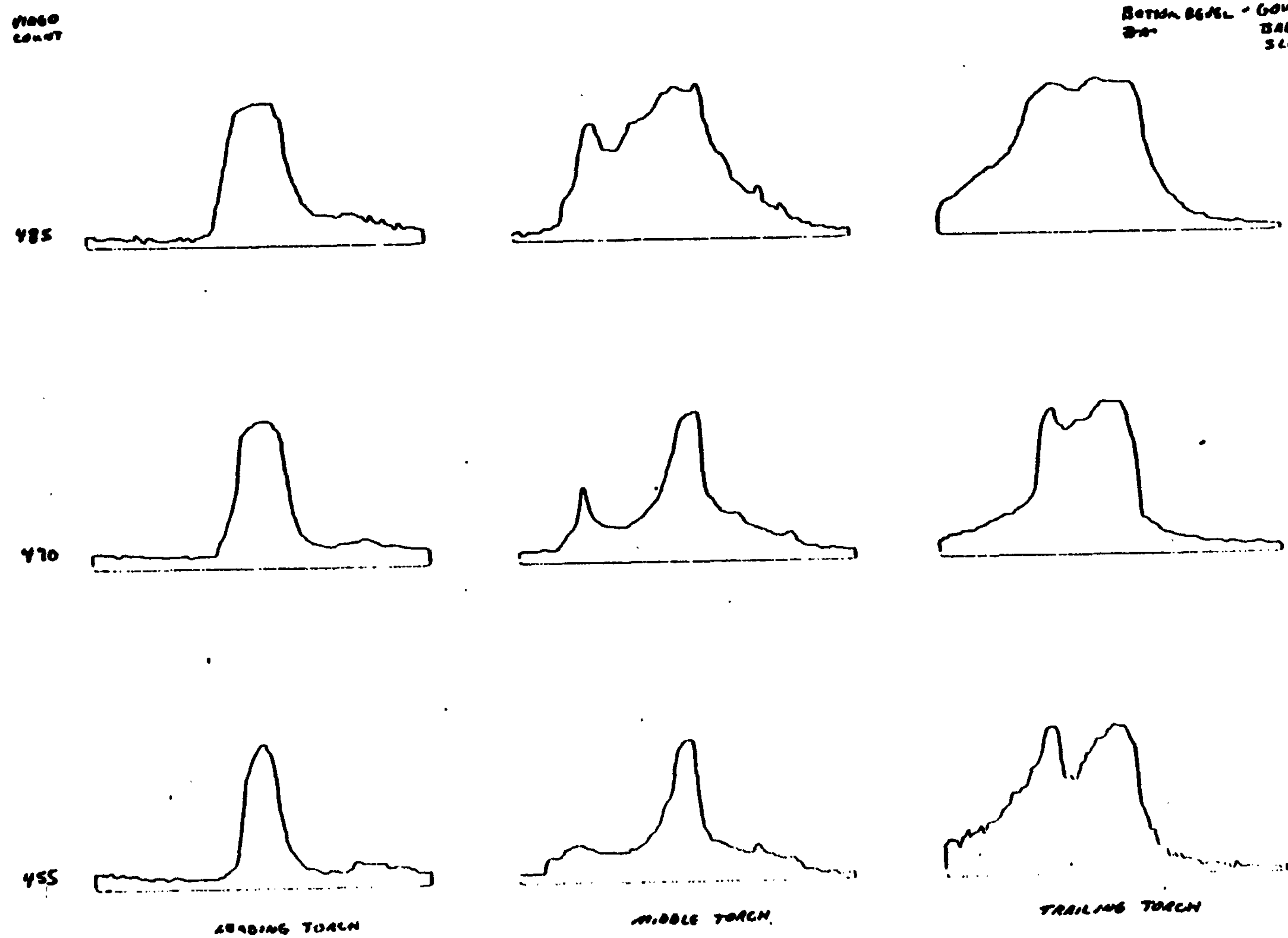
CUT # B-41
VIDEO CT. 43
VIDEO REEL # 8
(CUTTING OXY + SPEED)
P-65 F-57
12 IPM
Bevel cut

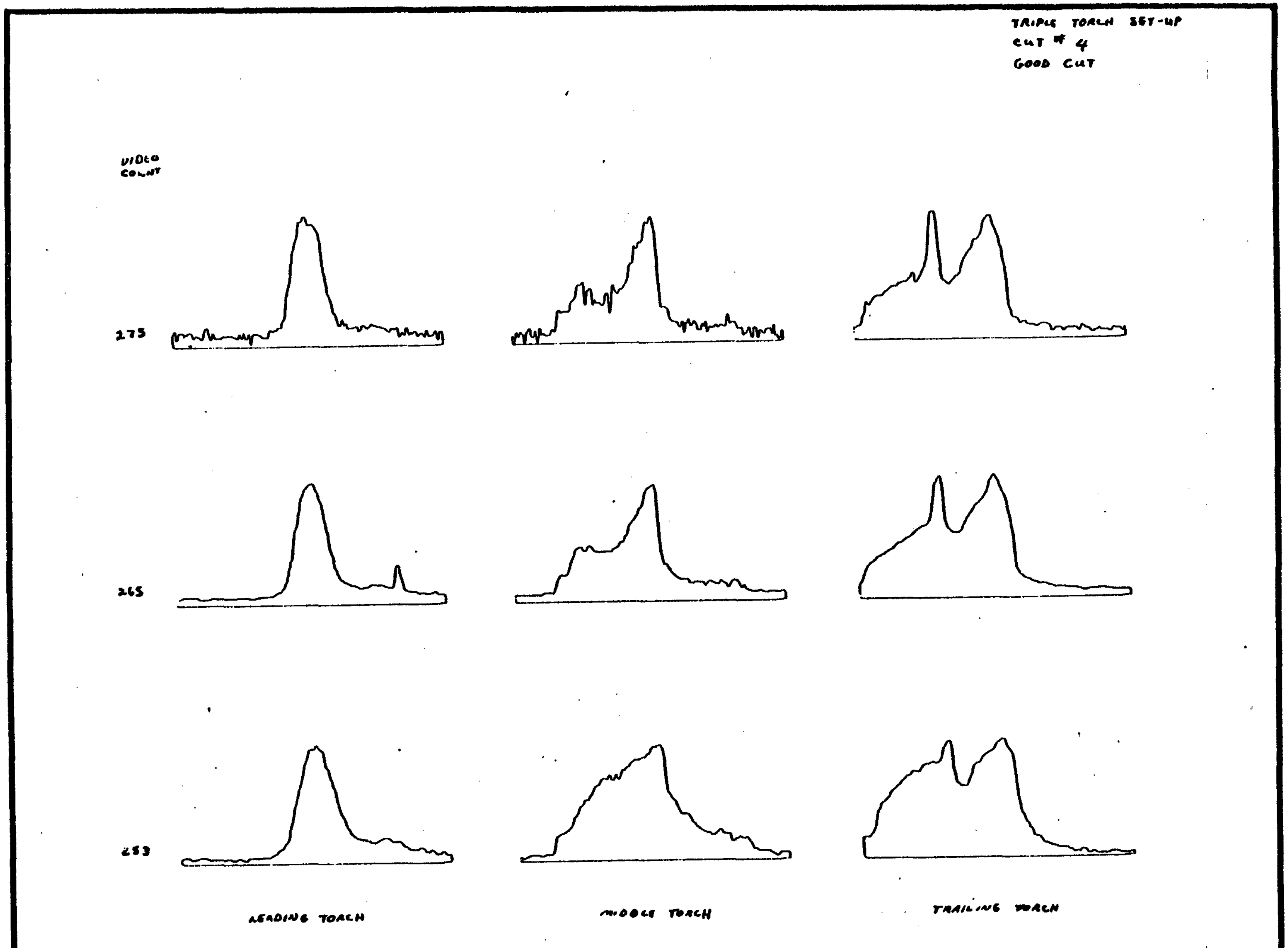


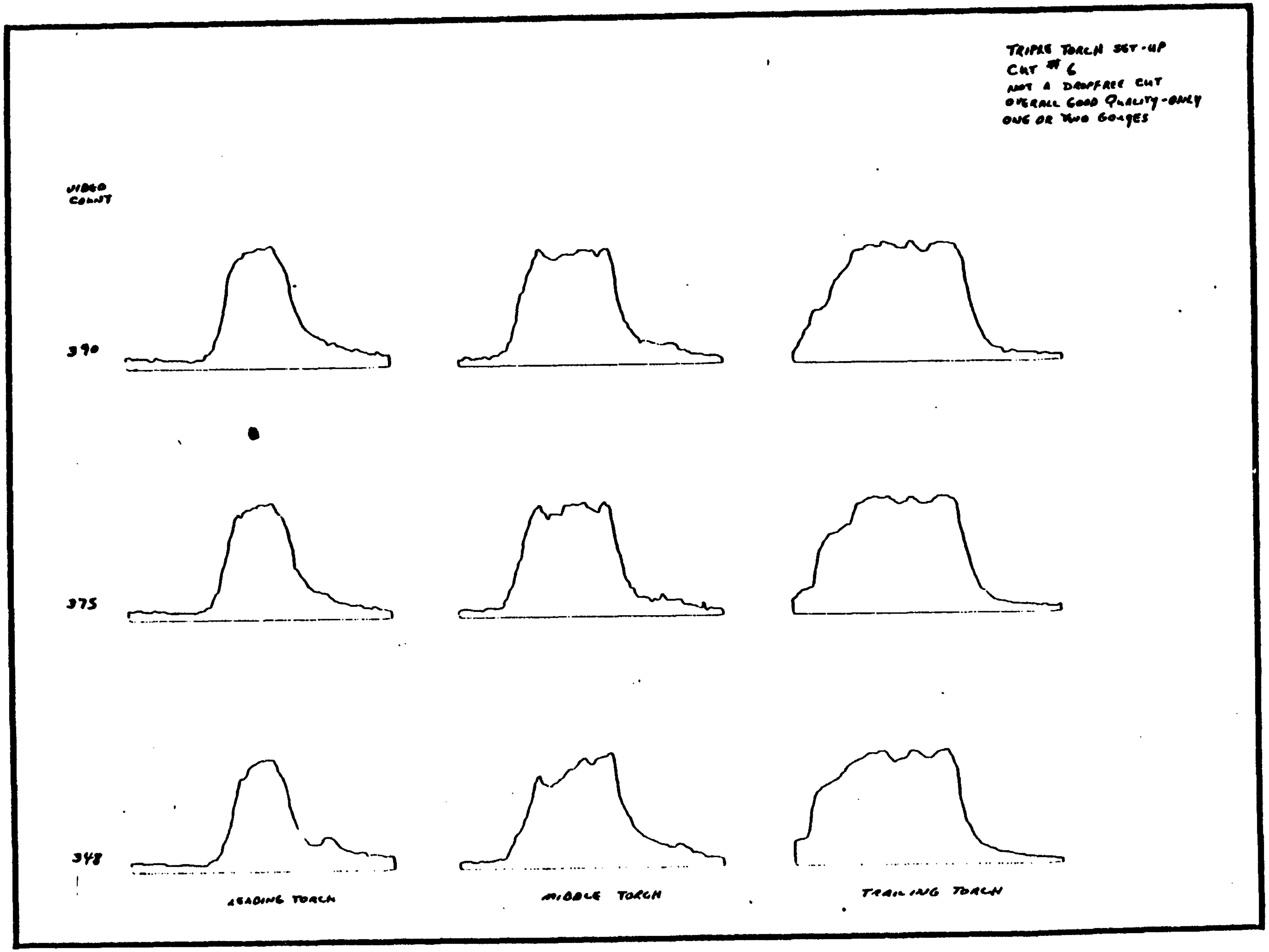


TRIPLE TORCH SET-UP
CUT # 9
8 IPM
NOT A DROP FREE CUT
TOP BEVEL-GOOD
LAND - OK
BOTTOM BEVEL - 1st 3" good & last 2" good
REST GOUGES
VIDEO COUNT
530
523
517
MIDDLE
TRAILING
LEADING
LEADING TORCH
MIDDLE TORCH
TRAILING TORCH

TRIPLE TORCH SET-UP
CUT #8
LEADING TORCH TIP CHANGED TO
GP #3
STARTED AT 8 IPM - SLOWED DOWN
AS CUT PROGRESSED
TOP BEVEL - GOOD
LAND - OK
BOTTOM BEVEL - GOUGED - GOOD AT START
BAD WHEN SPEED WAS
SLOWED DOWN




TRIPLE TORCH SET-UP
CUT # 4
GOOD CUT
VIDEO COUNT
275
265
253
LEADING TORCH
MIDDLE TORCH
TRAILING TORCH


TRIPLE TORCH SET-UP
CUT # 6
NOT A DROPFREE CUT
OVERALL GOOD QUALITY - ONLY
ONE OR TWO GOUGES
VIDEO COUNT
390
375
348
LEADING TORCH
MIDDLE TORCH
TRAILING TORCH